University of Alberta

Comprehensive Investigation and Testing of AOT Electrofloc^{PLUS} System for Treatment of Municipal Wastewater

by

Kai J. Nielson

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Abstract

The use of electrochemical principles for the treatment of wastewaters has fostered increased attention in recent years. This thesis examines one such technology termed the Electrofloc^{PLUS} wastewater treatment system developed by Applied Oxidation Technologies Inc. of Ladysmith, British Colombia. The application studied was its ability to treat municipal wastewater. The results of an extensive testing scheme showed that the technology was effective in the reduction of certain water quality parameters including total suspended solids (TSS) and total phosphorus (TP) as the unit was capable of meeting regulatory guidelines. While removals of chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5) were less impressive as the test unit was unable to treat the wastewater adequately to meet regulatory guidelines. Other considerations were also examined including the Electrofloc^{PLUS} treatment systems energy requirements. The results showed that energy consumption to be quite high relative to competing technologies.

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Abbreviations:

BOD$_5$ – 5-day biochemical oxygen demand, mg/L

C – Number of colonies counted

CBOD – Carbonaceous biochemical oxygen demand, mg/L

COD – Chemical oxygen demand), mg/L

D^2 – Index of dispersion

DAF – Dissolved air floatation

DOC – Dissolved organic carbon, mg/L

I – Current (amperes)

MLSS – Mixed liquor suspended solids

MWTP – Municipal wastewater treatment plant

n – Sample size

P – Power Consumption, watts

R – Resistance, ohms

s^2 – Estimate of the population variance

TBOD – Total biochemical oxygen demand, mg/L

TNTC – To numerous to count

TP – Total phosphorus, mg/L

TOC – Total organic carbon, mg/L

TSS – Total suspended solids, mg/L

U – Voltage (volts)

VSS – Volatile suspended solids, mg/L

$\bar{x}$ – Estimate of population mean

1.0 General Introduction

The idea of using electrochemical processes for treatment of wastewater has been around since the early 1900's but the technology is only presently being commercialized as earlier developments proved to be uneconomic. Improvements in process design have occurred in recent years making electrochemical processes an attractive alternative to a conventional wastewater treatment system in order to meet today's standards. The system tested during this project was the AOT Electrofloc^{PLUS} demonstration system developed by Applied Oxidation Technologies Inc. of Ladysmith, British Columbia. This electrochemical technology may be ready for scale-up and broader use.

Further research is required for the Electrofloc^{PLUS} technology to be accepted by the consulting industry and put forward to the BC Environment and other jurisdictions. Accordingly, this research project was to investigate the system performance and compare it to the current British Columbia effluent discharge requirements and those of other jurisdictions. The thesis also examines the energy consumption and other costs compared to alternative technologies. Additionally, the potential of creating new environmental problems or occupational hazards was also examined and discussed. This thesis increases the knowledge about the technology by defining its performance under different operational settings and helps to provide a better basis for judging the technology.

1.1 Research Objectives

Unfortunately, limited information is available on the Electrofloc^{PLUS} system's ability to treat municipal wastewater. Although research in Ladysmith, British

Columbia, is ongoing little is known (and nothing is published in a refereed scientific journal) in regards to the units process optimization and the specific energy requirements with varying municipal wastewater characteristics. Additionally, there is relatively little published in regards to similar technologies and their ability to treat municipal effluents. The primary objective of this thesis is to make a comprehensive review and investigation of the AOT Electrofloc^{PLUS} wastewater treatment technology and its ability to treat primary municipal effluent from the Goldbar wastewater treatment plant in Edmonton, Alberta, Canada and to put these capabilities into a context for comparison with pertinent regulations and its economic potential and opportunity for use in Canada. This will be discussed in terms of its capabilities with respect to chemical/physical parameters (such as TSS, pH, temperature, BOD_5, COD, TP, nitrogen forms, metals) and biological parameters including fecal coliforms, *Bacillus subtilis* spores (a surrogate for potential protozoan reduction) and *Cryptosporidium parvum* in comparison to existing regulations/guidelines. The unit's fundamental advantages and disadvantages will be discussed in terms of the discovered inputs/costs/energy requirements as well as pertinent design considerations in comparison to existing technologies and infrastructure used in British Columbia, and the rest of Canada. This independent based research and analysis will provide a part of a growing framework from which full scale use (and further development) of this new and innovative technology can be put forward to environmental regulatory agencies.

1.2 General Overview of Report

As part of the aforementioned objectives the following elements of the thesis are included:

- general review of current state of municipal wastewater treatment in Canada (existing treatment methods and treatment levels, regulatory requirements/guidelines, health and ecological considerations);
- discussion of electroflocculation issue's including the theory of the processes, impact of conductivity and application issues;
- review of pertinent documents and patents;
- experimental design and scope of research program;
- project testing methods;
- results / discussion (includes discussion of project limitations, how to further develop technology, where the technology is useful, what technologies may work in concert with this, improvements on this study); and
- conclusions/recommendations.

2.0 Literature Review

2.1 General Review of Wastewater Treatment

According to Gray (1999) the aims of wastewater treatment include:

(a) to convert the waste materials present in wastewaters into stable oxidized end products that can be safely disposed of to inland waters without any adverse ecological effects;

(b) to protect public health;

(c) to ensure wastewater is effectively disposed of on a regular and reliable basis without nuisance or offense;

(d) to recycle and recover the valuable components of wastewater;

(e) to provide an economic method of disposal; and

(f) to comply with legal standards and consent conditions placed on dischargers.

In attempting to accomplish these aims it is also important to consider local conditions and the receiving waters' use. Kinnicutt et al. (1911) wrote "The relative importance of freedom from solids, organic stability, and bacterial purity must be determined in each particular case by a study of local factors."

Various technologies and regulations have been developed over the years in Canada in order to meet the aforementioned objectives while giving consideration to local conditions and requirements. The Electrofloc^{PLUS} technology is one such recent development that can help meet the aims of wastewater treatment for certain municipalities and their local conditions. Traditional treatment technologies in Canada will be briefly discussed in this section as well as a discussion of important effluent issues including public health, aesthetics and ecological considerations. This section, along with section 2.2 (pertinent regulations), will provide the basis from which the Electrofloc^{PLUS} system performance can be judged.

2.1.1 Traditional Wastewater Technologies Used

Treatment of municipal wastewater has been typically categorized according to the number of conventional treatment processes which the raw municipal wastewater is exposed to. As such the following categories have been established within the scientific literature and within government publications to give an idea of treatment level including pre-treatment, primary treatment, secondary treatment, tertiary treatment and microorganism reduction. As new technologies have been developed and used these established categories have become less tied to a specific process and relate more to meeting specific effluent quality objectives. For purposes of this paper the following definitions from "Standards and Guidelines for Municipal Waterworks, Wastewater and Storm Drainage Systems" (AEP, 1997) will be used for this discussion.

Preliminary treatment is defined as screening and grit removal of large solids (AEP, 1997). Its purpose is to improve downstream treatment by preventing blockages, physical damage and to improving operating efficiency by slowing the accumulation of solids in channels, settling tanks and digesters. The process uses screen devices first (both coarse and fine screens) to remove debris and grit chamber to remove particles over 0.2 mm with a specific gravity of 2.65.

Primary treatment utilizes sedimentation to eliminate settleable solids, floating material and scum from raw wastewater (AEP, 1997). Technologies conventionally employed for this purpose include both horizontal (water flows in one end and leaves the other) and vertical flow tanks (water flows into the center and flows to the periphery of the tank). Sediments that settle to the tank floor are mechanically moved into hoppers and scum baffle/skimmer bars are used to move scum and flotables. The scum and sludge is then pumped for further treatment and disposal.

Secondary treatment is utilized to further remove pollutants to achieve lower concentrations of the parameters of concern through the use of a suspended growth system (typically an activated sludge process), a fixed film system (typically a rotating biological contactor) or a coupled system (AEP, 1997). These methods utilize biological processes to treat the water. Oxygen addition is generally required in order to meet the 5-day carbonaceous biochemical oxygen demand (CBOD) of the system. These biological methods conventionally used for secondary treatment operate significantly different than the Electrofloc^{PLUS} wastewater treatment system in that the Electrofloc^{PLUS} system does not utilize any biological processes for treatment.

Tertiary treatment entails effluent microorganism reduction and nutrient reduction (phosphorus and nitrogen forms) in addition to further reduction of CBOD and TSS (AEP, 1997). Typical technologies for phosphorus reduction include biological phosphorus removal (by utilizing organisms which take up large quantities of phosphorus and then removing these organisms) and chemical phosphorus removal (by the addition of metallic salts or lime). Ammonia removal is done biologically with the organisms *Nitrosomonas* and *Nitrobacter* which are slow growing and sensitive to temperature. Effluent microorganism reduction is typically achieved through one of UV radiation, chlorine, ozone and chlorine dioxide. The Electrofloc^{PLUS} system utilizes only ozone addition of the above conventional methods as part of its treatment process and the ozone addition is used more as a coagulant aid rather than for microorganism reduction.

It is suggested that the Electrofloc^{PLUS} wastewater treatment system may be able meet some or all of the treatment objectives of secondary, tertiary and microorganism reduction all in one step.

2.1.2 Public Health Considerations of Municipal Effluents

In western science the understanding of the potential impact of water contamination by municipal wastewater was first fully realized as a result of the Broad Street pump epidemic in London, 1854. In that year an Asiatic cholera outbreak occurred in the St. James Parish. The mortality was very disproportionate with other locations in London and an inquiry into the cause was commissioned. As a result of the inquiry it was discovered that a defective cesspool was allowing the municipal sewage to infiltrate into the ground and contaminate the Broad Street pump's water resulting in high exposure and death (Revelle and Revelle, 1981). This experience resulted in a greater understanding of the importance of proper disposal of municipal wastewaters.

Today's science has advanced greatly since 1854; however, the same principles that were discovered back then still apply today. From a public health perspective municipal wastewaters are of concern because they contain high concentrations of pathogenic organisms which upon release could come into contact with humans and cause illness. Table 2-1 gives the potential infectious agents present in raw domestic wastewater.

It is reported that preliminary and primary treatment processes used in wastewater treatment are capable of destroying or removing a large portion of bacteria. Removal or destruction of around 75% of the bacteria has been reported due to the settling mechanism alone (Liu and Liptak , 2000). However, these levels of removal are considered inadequate and many treatment facilities (including the Goldbar Wastewater Treatment plant in Edmonton) utilize a final microorganism reduction process to further reduce pathogen levels before release to the natural environment. Conversely wastewater lagoons do provide sufficient pathogen elimination so that a final microorganism reduction process is not usually desired or required. Table 2-2 shows typical removals of various pathogens for different treatment levels as summarized by the National Research Council (NRC, 1996) and Feachem et al. (1983).

Table 2-1 Potential Infectious Agents in Present in Raw Domestic Wastewater

Organism	Disease	Remarks
Bacteria		
Escherichia Coli	Gastroenteritis	Diarrhea
Legionella pneumophila	Legionellosis	Acute respiratory illness
Leptospira (150 spp.)	Leptospirosis	Jaundice, and fever (Weil's disease)
Salmonella typhi	Typhiod fever	High fever, diarrhea, and ulceration of small intestine
Salmonella (1700 spp.)	Salmonellosis	Food poisoning
Shigella	Shigellosis	Bacillary dysentery
Vibrio cholerae	Cholera	Extremely heavy diarrhea and dehydration
Yersinia enterolitica	Yersinosis	Diarrhea
Viruses		
Adenovirus (31 types)	Respiratory disease	
Enterovirous (67 types)	Gastroenteritis, heart anomalies, and meningitis	
Hepatitis A	Infectious hepatitis	Jaundice and fever
Norwalk agent	Gastroenteritis	Vomiting
Reovirus	Gastroenteritis	
Rotavirus	Gastroenteritis	
Protozoa		
Balantidium coli	Balantidiasis	Diarrhea and dysentery
Cryptosporidium	Cryptosporidiosis	Diarrhea
Entamoeba histolytica	Amrbiasis	Prolonged diarrhea with bleeding and abscesses of the liver and small intestine
Giardia lamblia	Giardiasis	Mild to severe diarrhea, nausea, and indigestion
Helminths		
Ascaris lumbricoides	Ascariasis	Roundworm infestation
Enterobius vericularis	Enterobiasis	Pinworm
Fasciola hepatica	Fascioliasis	Sheep liver fluke
Hymenolepis nana	Hymenolepiasis	Dwarf tapeworm
Taenia saginata	Taeniasis	Beef tapeworm
T. solium	Taeniasis	Pork tapeworm
Trichuris trichiura	Trichuriasis	Whipworm

Adapted from: Metcalf & Eddy, Inc., (1991), Lui & Liptak, (2000), Feachem et. al. (1983)

Table 2-2 Wastewater Treatment Levels and Associated Levels of Microorganisms Typically Found

	Number Per 100 ml				Log Reduction
Microbe	Raw Wastewater	Primary Treatment	Secondary Treatment	Tertiary Treatment	Waste Stabilization Pond
Fecal coliform (MPN)	1,000,000,000	10,000,000	1,000,000	<2	4 log to Complete
Salmonella (MPN)	8,000	800	8	<2	4 to 6 log
Shigella (MPN)	1,000	100	1	<2	4 log to Complete
Enteric virus (PFU)	50,000	15,000	1,500	0.002	1 log to 4 log
Helminth ova	800	80	0.08	<0.08	Complete
Giardia lamblia cysts	10,000	5,000	2,500	3	Likely Complete

Notes: Tertiary treatment includes coagulation, sedimentation, filtration and disinfection.
Mesophilic anaerobic digestion used for sludge digestion.
Waste Stabilization heavily dependant on temperature and retention times

Sources: NRC (1996) and Feachem et al. (1983)

Effective microorganism reduction of municipal effluents allows for easier water treatment for municipalities that may be downstream from a treatment plant's outfall. Additionally effective microorganism reduction allows for greater water usage opportunities for the receiving waters that might not otherwise be possible such as boating, swimming and irrigation. For additional discussion on the microbial health aspects of municipal effluents the reader is directed to works by Feachem et al. (1983).

Although microbiological contamination is of greatest concern to public health, toxicological impacts on the receiving environment are also of some concern as contaminants such as heavy metals can be passed to fish and/or shellfish which are then caught for human consumption.

2.1.3 Aesthetic Considerations

Aesthetic considerations primarily revolve around both offensive sights and odor control. For example effective wastewater collection and treatment can mitigate the aesthetic impacts municipal effluents have on the environment. For example efficient nutrient removal can slow the eutrophication process in natural waters, which would reduce aesthetic and recreational interferences such as the presence of algal mats, decaying algal clumps, odors and discoloration caused by the release of the nutrients (Thomann and Mueller, 1987).

Environment Canada (2001a) reports a case study documenting some of the potential negative impacts from aesthetic problems caused by the lack of treatment of municipal effluents. St. Johns, Newfoundland and the surrounding municipalities release 120 million litres of raw sewage and stormwater runoff into the local harbor every day. Much of the TSS ends up on the harbor floor were it is decomposed by anaerobic bacteria. This results in highly odorous hydrogen sulfide gas. This gas accumulates and when large ships churn up the sediment the gas is released resulting in odors strong enough that many people on the passing ships feel ill. Additionally, debris from untreated wastewater also remains in the harbor and many tour boat operators report that tourists complain when they spot such wastes including condoms, sanitary napkins, tampons, toilet paper, and other flushable material. These types of aesthetic impacts from the lack of sufficient treatment of municipal wastes clearly degrades the quality of life of local residents while also hurting the tourism potential of the area. Recently, the second largest cruise ship in the world the *Norwegian Sky*, visited this harbor and contributed over $200 000 to the local economy but the harbor's appeal for attracting similar and repeat visits seems stunted by the water quality in the harbor.

2.1.4 Ecological Considerations

The ecological considerations in regards to municipal effluents can be far reaching. The impact of municipal effluents on the environment can be seen from very simple cause and effect associations in addition to very complex interrelationships amongst various components of the environment. This section will briefly highlight some of the potential impacts that municipal wastewater can have on the ecological balance of the receiving ecosystem.

The environment can be impacted from municipal effluents due to three of its intrinsic components including the chemical, physical and biological nature of the released wastewater (Environment Canada, 2001a). Chemical problems include increases in nutrients, toxic contaminants and endocrine disrupting chemicals. Physical problems include increased water flow, increased suspended solids, heating of receiving waters and floating debris. Biological concerns include the potential for the introduction of high levels of pathogens into receiving environment and high BOD levels. Table 2-3 adapted in part from Environment Canada (2001a) and Chambers et al. (1997) shows the potential ecological impacts created from these contaminants with case examples. Table 2-3 is meant as guide only and not as an exhaustive list of all potential ecological problems.

Table 2-3 Possible Ecological Impacts of Municipal Effluents

Chemicals	Water quality, habitat	Plants	Animals	Case Examples
Nutrients (Nitrogen and Phosphorus)	• reduction of oxygen due to decay of plant matter • water clarity reduced • accelerated eutrophication	• composition of algal species changes • enhanced growth of submerged weeds • expansion of algal biomass and potential development of toxic blooms	• changes in food supplies for herbivores causes modification in species composition • decreased productivity and survival rates of invertebrates and fish caused by oxygen depletion	• Eutrophication to South Saskatchewan River downstream Saskatoon (Chambers, 1993; Chambers and Prepas, 1994) downstream Duncan-North Cowichan MWTP, B.C. (Perrin et. al. 1988), Georgian Bay, Lake Huron (Nicholls and Heintsch 1992) and Lake Ontario (Sly 1991).
Toxic Contaminants	• higher concentrations of toxic contaminants in sediments and water	• reduced species abundance and diversity caused by acute or chronic toxicity (affecting reproduction, growth, • bioaccumulation of toxins	• reduced species abundance and diversity caused by acute or chronic toxicity (affecting reproduction, growth, survival) • bioaccumulation of toxins • biomagnification of toxins at upper food chain levels	• Bioconcentration of some metals and fish in the lower Fraser River B.C. (Environment Canada 2001a) • Bioaccumulation of Hg in fish and invertebrates 1-3 km below Macauley and Clover points MWTP in Victoria B.C. (Colodey et al. 1992)
Endocrine Disrupting Chemicals			• deformities and embryo mortality in birds and fish • reproduction and development is impaired in fish • lowered immune and thyroid functions in fish-eating birds • male fish and reptiles are feminized	• Emerging issue growing evidence suggests municipal effluents can contain endocrine disruptors in fish perhaps from non-ionic surfactants in detergents (Chambers et al 1997)

Table 2-3 Possible Ecological Impacts of Municipal Effluents (continued)

Physical

	Water quality, habitat	Plants	Animals	Case Examples
Total Suspended solids	• water clarity lowered • adsorbed contaminants transported • sedimentation- related changes to water flow	• photosynthesis is lowered and plant growth diminished due to reduced water clarity	• spawning grounds blanketing • reduced growth or survival of species • blockage of dispersal routes by accumulated sediments	• Intertidal sand flats in outer estuary of Fraser River B.C. extensively degraded when Iona MWTP was discharging there (Birtwell et al. 1988)
DO Stress	• lower levels of dissolved oxygen in water column and sediments from buildup of oxygen-consuming matter		•decreased biodiversity, fish kills and loss of species.	• Iona MWTP discharges onto intertidal flats causing daily mortality of fishery resources (Crab, salmon and flounders) (Birtwell et al. 1983)
Heating of the receiving water	• water temperature increase	• progression from cold-water to warm- water algal species	• progression from cold-water to warm-water fishery	
Floating debris			• entanglement causing loss of normal functions lead to starvation and exhaustion. • blocking of digestive tract from the intake of debris	

Biological

Pathogens (bacteria, virus's, protozoa)	• enhanced levels of pathogens in sediments and water		• enhanced levels of pathogens in filter-feeding shellfish (bivalve molluscs)	• Lower Fraser River and estuary, B.C., has had fish and shellfish restrictions (Birtwell et al. 1988) • Beach closures around the Canadian Great lakes (Edsall and Charlton, 1996)

Primary Sources: Chambers et al 1997, Environment Canada 2001a

2.2 Pertinent Regulations/Guidelines Regarding Municipal Effluents

The objective of this project was to determine the effectiveness of the test unit in treating primary municipal effluent. As such the technology is proposed as an alternative to conventional biological secondary treatment systems for municipal wastewaters and therefore its performance should meet or exceed the performance standards outlined for secondary biological treatment systems in order to be accepted as a stand alone replacement. This project will determine if it can meet these regulations and if so under what wastewater conditions and test unit inputs. It is important to also consider that other factors will impact this technology's suitability aside from meeting the following standards. These standards are meant as only a starting point from which to judge the Electrofloc^{PLUS} technology. Also, it is important to consider that for all the mentioned standards there are often exceptions or stricter requirements depending on the exact site details of the discharge (i.e. take into account health, aesthetic and ecological considerations of the discharge site).

2.2.1 British Columbia

In British Columbia the standards for municipal discharges are defined in "Waste Management Act Municipal Sewage Regulation" (WMA, 1999). The standards differentiate between different receiving waters and the volume of water being treated. The standards also are dependant on the fluctuations of the flow to the MWTP. During normal flows at least secondary treatment is required for all MWTP discharging into freshwater and larger MWTP (max. daily flow ≥ 50 m^3/d) discharging into the ocean. Mid sized MWTP (max. daily flow <50 m^3/d and ≥ 10 m^3/d) discharging into open marine environment only require primary treatment but if discharging into an embayed marine water they require secondary treatment as well. Smaller treatment plants (max. daily flow < 10 m^3/d) only require septic treatment if discharging into a marine environment. Secondary treatment standards for larger MWTP discharging into embayed marine water during normal flows is given as part of the summary Table 2-4 at the end of this section. Values for other municipal discharges requiring secondary treatment are similar.

2.2.2 Alberta

In Alberta the standards for municipal discharges are defined in "Standards and Guidelines for Municipal Waterworks, Wastewater and Storm Drainage Systems" (AEP 1997). Standards are defined for small systems (municipal population <20,000) and for large systems (municipal population >20,000). The standards for secondary effluents are slightly tougher for larger systems but are pretty similar all round. This document also reports treated effluent standards required for wastewater irrigation which reports an EC standard of <2.5 ds/m.

2.2.3 Ontario

The Ontario Minstry of Environment (MOE) has procedure F-5-1 "Determination of Treatment Requirements for Municipal and Private Sewage Treatment Works Discharging to Surface Waters" (OMOE, 1994) to define the level of treatment required by municipalities. It reports "Guideline F-5 takes the approach that all sewage treatment works shall provide secondary treatment or equivalent as the "normal" level of treatment, unless individual receiving water assessment studies indicate the need for higher levels of treatment." It goes on to report design objectives for $CBOD_5$, TSS and TP and effluent guidelines for $CBOD_5$ and TSS for different "secondary treatment technologies". Electroflocculation is not currently listed in this document as a secondary treatment technology.

2.2.4 USA

The federal regulations for municipal discharges in the USA are defined as part of the Code of Federal Regulations (CFR, 2002) under the part heading "Secondary Treatment Regulation". The document lists simple values for 7 day and 30 day average $CBOD_5$ or BOD_5, 7 day and 30 day average TSS and pH limits. It also lists a variety of exceptions and provision to these rules.

2.2.5 European Union

The European Union has the document "The Urban Waste Water Treatment Directive" (EU, 1991) to control municipal effluents. Article 4 point 1 indicates "Member States shall ensure that urban waste water entering collecting systems shall before discharge be subject to secondary treatment or an equivalent treatment." The regulation goes on to give parameter values subject to article 4. The document also indicates in article 6 that less stringent requirements for non-sensitive marine discharges. These values are unique in that they also include a percent reduction requirement. It is important to note that individual country members may have more stringent standards. These values can be found in Table 2-4.

Table 2-4 Municipal Effluent Standards for Various Jurisdictions

Parameter	Ab. Env. (1)	B.C Marine (2)	Ontario (3)	USA (4)	EEC (5)
BOD_5 (6)	20 mg/L	45 mg/L	25 mg/L	30 mg/L (85%)*	25 mg/L (70 to 90%)*
COD	(45 mg/L)**	(102 mg/L)**	(57mg/L)**	(68 mg/L)**	125 mg/L (75%)*
TSS	20 mg/L	45 mg/L	25 mg/L	30 mg/L (85%)*	35 mg/L (90%)*
TP	1 mg/L	1 mg/L	1 mg/L	None Found	1 mg/L (9) (80%)*
pH	6.5 to 8.5	6 to 9	None Found	6 to 9	None Found
Fecal Coliforms	200/100 mL	200/100 mL (8)	None Found	None Found	None Found
Ammonia/Nitrogen Forms	(7)	(7)	(7)	None Found	15mg as TN (9) (70-80%)*

*Bracketed percent data indicates an additional percent removal requirement
**Assuming COD/BOD = 2.27

(1) Values given are for large municipalities (municipal population >20,000) for smaller municipalities $CBOD_5$ and TSS are 25 mg/L.
(2) Values given are for large MWTP (max. daily flow ≥ 50 m3/d) with embayed marine waters. Other values are similar.
(3) BOD_5 and TSS givens as Guideline, TP is given as Design Objective for a Conventional Activated Sludge with TP removal
(4) Values indicate 30 day average requirements
(5) European Economic Community directive 91/271/EEC requirements as per article 4 & 5. Article 6 allows for relaxed requirements for non-sensitive marine discharges
(6) BOD_5 values refer to TBOD for B.C and USA. For Alta.,Ont. and EEC BOD_5 values are as $CBOD_5$
(7) Need assessed on a site specific basis
(8) More stringent standards required if discharging into shellfish area (14/100ml) or with 300m domestic water extraction site(2.2/100ml)
(9) For WMTP servicing between 10 000 - 100 000

Sources: European Union (EU). 1991;Code of Federal Regulations (CFR). 2002;Ontarion Ministry of Environment (OMOE), 1994;Waste Management Act (WMA), 1999;Alberta Environmental Protection (AEP), 1997

2.3 Review of the Current State of Municipal Wastewater Treatment in Canada

Due to technical reasons that will be discussed later in this thesis the ability of the Electrofloc^{PLUS} treatment system to operate with low power consumption is related to the ability to discharge to a saline environment. This section will outline the state of wastewater treatment in Canada to help identify the potential locations for the adoption of the technology. The section also provides a basis from which to understand the current treatment situation in Canada and how this new technology can fit into the current situation.

In Canada the volume of wastewater treatment has steadily grown since the turn of the century. Approximately 75% of Canadians (22.5 million people) residing in 1200 municipalities utilize municipal sewer systems (Environment, Canada 2001b). Currently, it has been estimated that 96.6% of the Canadian population with municipal sewer service has some form of wastewater treatment. Additionally, there has been a steady increase over the past fifteen years towards higher levels of treatment as 78 % of the serviced population has secondary treatment or better while only 69% had this level of treatment in 1994 and only 56% in 1983 (Environment Canada, 2001b). However, still 19% of the serviced population still has only primary treatment and 3% has no treatment at all.

It is also important to note that there are striking regional disparities in levels of treatments. British Columbia has shown drastic improvements in the levels of wastewater treatment over the last few years while Atlantic Canada still has large proportions of the population without any treatment at all as treatment levels have seen little improvement over the last 20 years. This region relies heavily on the dilution capacity of the ocean as the solution to wastewater problems. Although nationally 96.6% of the population is served by some form of treatment in Atlantic Canada that number drops to 55%. It is also important to note that B.C and Quebec have a relatively large proportion with just primary treatment and very little with tertiary treatment. In contrast both the Prairies and Ontario both have very low proportions of no treatment and primary treatment and relatively high proportions with secondary and tertiary treatment.

The final note on the state of wastewater treatment in Canada is the disparity in treatment levels for inland releases verses ocean releases of wastewater. As can be seen from Figure 2-1 over 80% of wastewater systems that release water inland have at least secondary treatment while the majority of municipal system which discharge into the ocean have only primary treatment or less.

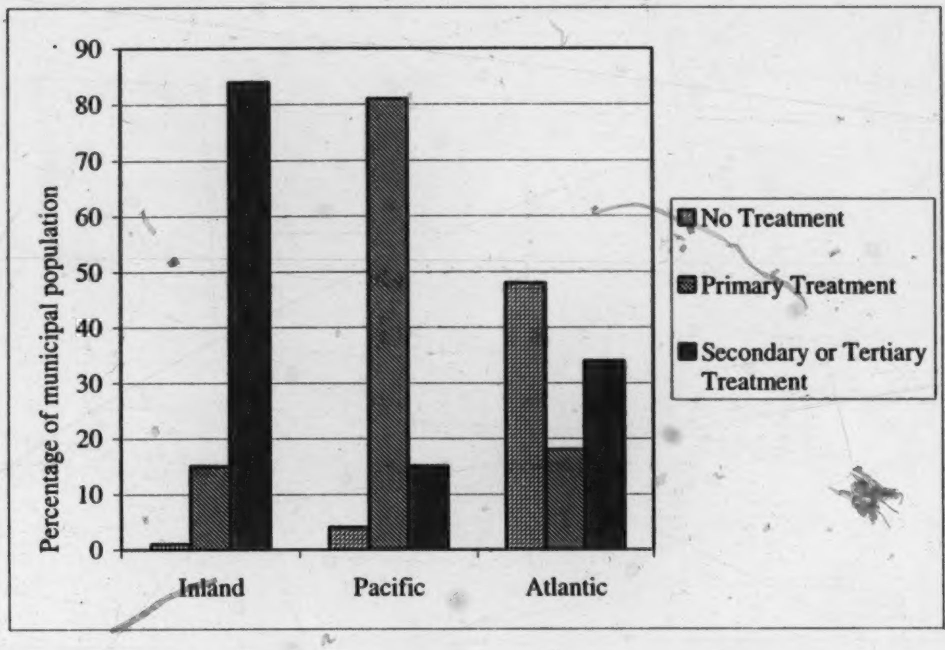

Figure 2-1 Level of Treatment of Municipal Wastewaters in Canadian Coastal and Inland Receiving Waters, 1999, Adapted from Environment Canada (2001a)

The state of wastewater treatment in Canada shows a trend towards greater treatment levels across the nation. Additionally, this section suggests that the principal areas requiring greater treatment include coastal releases on the Atlantic and Pacific Oceans. Of particular interest is the increase in treatment levels found for wastewater discharges to the Pacific Ocean in British Colombia as the majority of discharges currently have primary treatment and as discussed in section 2.2.1 greater treatment is required. Due to the demand for greater treatment in this region and for technical reasons allowing lower power consumption at any given treatment level when releasing to a marine environment, this appears to be a potential market niche for the Electrofloc^{PLUS} technology. Additionally, much of this region has high potential for hydropower which is a low cost power source making electrochemical processes more viable. Inland regions such as Alberta and Ontario generally have the infrastructure in place for greater levels of treatment already and for technical reasons would require higher Electroflоc^{PLUS} energy inputs when compared to ocean discharges. Also, land prices in these regions are generally lower which allow for the use of inexpensive and effective wastewater lagoons. In Atlantic Canada, ocean releases still have significant volumes of untreated wastewater and the movement towards increased treatment is relatively slow compared to Pacific coast discharges. However, this area may also benefit from the development of this technology as it could potentially allow for low cost advanced treatment of wastes currently causing health risk, aesthetic and ecological problems in the surrounding ocean.

2.4 Introduction to Electroflocculation

This section will discuss the basic concepts involved in the electroflocculation process. Essentially the Electrofloc^{PLUS} system uses electrochemical principles to destabilize pollutant particles allowing for their agglomeration while these agglomerated particles attach to small gas bubbles created during the electrochemical reaction resulting in the flotation of the various pollutants. The treated wastewater can then be separated from the concentrated pollutants on top. The following discussion will expand on this simplified process description to define in greater detail the mechanisms at work. The topics will include a basic review of the theory behind electroflocculation, the impacts of the different wastewater conditions on the process and application design issues. The discussion will primarily revolve around the technical concepts most pertinent to the Electrofloc^{PLUS} system and its use with treating municipal wastewater.

2.4.1 Theory

Two main colloidal chemistry principles are responsible for controlling the floc formation in the alternating current process. The neutralizing of suspended particles surface charge by subjecting the particles to an electrical field in a turbulent stream is the first principle, while the second principle entails very small quantities of metal hydroxides being produced from the dissolution of the electrodes to help flocculate the suspended particles (Barkley et al., 1993).

The electrocoagulation/flocculation process entails passing current through the water sample in an undivided cell with usually an Al or Fe anode as is the case of the Electrofloc^{PLUS} test system. Aluminum commonly is the best anode materials as it is the most affordable material that provides trivalent cations. Iron also provides trivalent cations however; iron typically shows inferior performance to aluminum although under certain wastewater conditions it may be more efficient (detailed work with municipal effluents comparing aluminum and iron electrodes is not available and as such this will be examined as part of this thesis). Most other affordable materials typically release bivalent cations, which are less preferred as they have a lower ability to adsorb onto particles in the water than do trivalent cations (Koren and Syversen, 1995). The trivalent cations have a higher charge density, which allows for the superior adsorption capabilities.

The design of the electrochemical cells can follow numerous different possibilities. Pletcher and Wienberg (1992a) discussed in detail the different theories and considerations in regards to electrochemical cell design for environmental applications. Considerations mentioned by Pletcher and Wienberg (1992a) for cell design include material for the electrode, materials for the cell body, method and materials for gasketing, design of turbulence promoter, configuration of electrolyte distributors, internal and external manifolding, electrolyte flow regime (series vs. parallel flowrate, with vs. without recycle, etc.), monopolar vs. bipolar electrical connection, inter-electrode gap, electrode areas, and electrode shape and form. The electrochemical cell of the test unit used in this project is proprietary and, therefore, its precise design will not be described although it is comprised of aluminum or iron electrodes depending on the configuration.

The electroflocculation process entails the addition of an electrical current to sacrificial electrodes, as discussed, made of aluminum or iron. This is done within a highly turbulent electrochemical cell with a positive anode and negative cathode. The dominant reactions at the anode and cathode are (Donini et al., 1994):

$$Al_{(s)} = Al^{3+} + 3e- \qquad \text{anode} \qquad (2\text{-}1)$$

$$2H_2O + 2e- = H_{2(g)} + 2OH^- \qquad \text{cathode} \qquad (2\text{-}2)$$

Additionally, the anode will be dissolving chemically:

$$Al_{(s)} + 3\,H_2O = Al(OH)_3 + 1.5\,H_{2(g)} \qquad (2\text{-}3)$$

The aluminum ions serve to neutralize the electrostatic charges on the suspended solids and allow for agglomeration. This charge neutralization process is similar to the mechanism that causes charge neutralization in conventional chemical coagulation the main difference being the source cause of the neutralization (i.e added ionically in the electroflocculation process while added chemically in conventional treatment). Standard water treatment information sources discuss the coagulation process in detail including AWWA (1990) and Metcalf and Eddy (1991).

Electrocoagulated floc differs significantly from floc formed in chemical coagulation. The advantage of electrocoagulated flocs over typical alum treatment include flocs that contain less bound water and are more shear resistant (Barkley et al. 1993). Also it is reported in the literature (Donini et al., 1994) that electrolytically added aluminum ions are much more active than chemically added aluminum ions thus the process can treat a number of different pollutants that could not normally be handled by chemical flocculants.

The hydrogen gas produced at the cathode (equation 2-2) captures coagulated agglomerates resulting in their flotation to the surface of the water very similar to a dissolved air flotation unit (DAF). The electroflocculation unit can be used as an alternative to DAF when the full process is designed for such removals. Just like a DAF unit the system could be designed to remove the surface pollutants without the use of filters leaving clean treated water underneath. Discussion on the application issues related to the hydrogen bubbles and their potential for solids removal via flotation will be presented later as a part of application issues.

2.4.2 Wastewater Characteristics

The specific chemical make up of the water used in electroflocculation will impact the process performance. However, little is known about the effects and interactions among components that impact performance aside from the impact of conductivity (discussed later) and pH which various academic sources say any pH in the range of 4 to 11 all work similarly in electroflocculation. The ability of other components such as TSS to aid or hinder process performance is not well understood nor is the impact of the interactions amongst different components well understood.

Some typical conductivities of various water streams can be found in the following table.

Table 2-5 Conductivity of Various Waters

Water	Conductivity	units	Reference
Purified Water	0.055	uS/cm	Accumet (1987)
Power Plant boiler water	0.055 to 1	uS/cm	"
Deionized Water	0.1 to 10	uS/cm	"
Distilled Water	0.5	uS/cm	"
Kootenay River at Creston	75 to 250	uS/cm	Webber (1996)
Thompson River at Spences Bridge	70 to 130	uS/cm	Webber (2000)
Fraser River at Hope	75 to 175	uS/cm	Holms (1997)
Columbia River at Revelstoke	100 to 150	uS/cm	Holms (1999)
Fraser River at Marguerite	110 to 250	uS/cm	Holms et al.(1996)
Restaurant Wastewater (western restaurant)	260 to 450	uS/cm	Chen et al. (2000)
Restaurant Wastewater (fast food)	250 to 710	uS/cm	"
Drinking Water (700 us/cm aesthetic criterion)	0.3 to 1	mS/cm	Accumet (1987)
Gold Bar PE (Edmonton Wastewater)	0.8 to 1.1	mS/cm	n/a
0.01M KCl (standard used)	1.4	mS/cm	Accumet (1987)
Gold Bar PE (with 2.6 g salt/L added)	5.0 to 5.3	mS/cm	n/a
Ocean Water	53	mS/cm	Accumet (1987)

The project used municipal wastewater, primary effluent for the majority of the testing because this stream was of interest as a potential option for the electroflocculation process on a full scale (i.e. replace conventional secondary treatment). The primary effluent wastewater used for this project was collected from the Gold Bar Wastewater Treatment Plant. The average concentrations in 1999 for various parameters of Gold Bar primary effluent can be found in Table 2-6.

Table 2-6 1999 Parameter Averages for Gold Bar WWTP Primary Effluent

Parameter	Conc. (mg/L)
TSS	102
BOD_5	140
COD	306
COD - soluble	118
Ammonia	22.1
TKN	35.8
TP	5.6

The conductivity of the wastewater after sampling for this project ranged from 800 µs/cm to 1100 µs/cm. Specific characteristics of each wastewater tested were analyzed at the time of the test run.

2.4.3 Effect of Source Water Conductivity

The conductivity of the source water is an important component especially in regards to this project as the conductivity directly impacts the amount of energy required for any given level of performance. The power consumption of the electrochemical cells can be expressed as (Koren and Syversen, 1995):

$$P = U \times I \tag{2-4}$$

Where P = power consumption (W), U = Voltage (V) and I = current (A).

Ohm's Law states that:

$$U = R \times I \tag{2-5}$$

Where R = resistance (Ohms).

Using this relationship it is possible to rewrite equation (2-4) as:

$$P = R \times I \times I = R \times I^2 \tag{2-6}$$

$$P = R \times I \times I \times (R/R) \tag{2-7}$$

$$P = R \times I \times R \times I / R \tag{2-8}$$

$$P = U \times U / R \tag{2-9}$$

$$P = U^2/R \tag{2-10}$$

Equation 2-6 shows that by reducing the resistance in the electrolyte it is possible (by also lowering the driving volts) to decrease the power consumption without changing the current and the resulting degree of separation. As the conductivity of the electrolyte increases the power required for any given degree of separation decreases (Koren and Syversen, 1995). In equation (2-10) we see that by lowering the resistance while keeping the volts constant the power consumption will increase, the current in the electrolyte will also increase, leading to an improvement in the water quality. Thus, for systems discharging into the ocean, addition of a certain volume of seawater or salt (NaCl) to raise the conductivity to an optimal level may be desirable to reduce the resistance (increase the current) without increasing the driving volts. The salt acts in the same way as increasing the driving volts. By using relationships (2-4) and (2-5) it is possible to determine the equivalent amount of increase in driving volts required to obtain a certain performance level to the actual increase in conductivity from adding the salt. If the conductivity were doubled (i.e resistance is cut in half) the performance would improve without increasing the driving volts thus higher quality effluent is obtained with relatively small increases in power consumption. This improvement in performance due to conductivity increase can be directly related to what driving volt increase would be required to yield the same performance without the increased conductivity. Once the increase in the required volts is determined the increase in required power consumption can also be determined by multiplying the equivalent driving volts required by the actual current obtained in amperes to get the equivalent necessary power in watts. This power increase is much greater than the power increase caused by adding salt, as both the driving volts and the amperes will increase to improve performance whereas when salt is added the amperes increase and performance is improved without increasing the volts.

To illustrate this point a hypothetical example using a wastewater with an initial conductivity of 1000 µs/cm will be used. In this example it is assumed that the measured amperes applied for the wastewater would be 16 A during its pass through the electroflocculation treatment system. This hypothetical treatment system is also assumed to have 32 driving volts available. In order to increase the amperes applied in this system two solutions are possible. The first solution would be to raise the conductivity of the wastewater by the addition of salt and the second solution would be to increase the driving volts. The required increases can be calculated as follows assuming 64 A as the desired final level for the amperes applied.

Situation A – Increase the conductivity:

Ohm's law

$R_{(actual)} = U / I$ (2-11)

$R_{(actual)} = 32\ V / 16\ A = 2.0\ ohm$

$R_{(desired)} = U / I$ (2-12)

$R_{(desired)} = 32\ V / 64\ A = 0.5\ ohm$ → *Driving volts remain at 32 V in this scenario

$Conductance_{(actual)} = 1 / R = 1 / 2.0\ ohm = 0.5\ Siemens$

$Conductance_{(desired)} = 1 / R = 1 / 0.5\ ohm = 2\ Siemens$

$\text{Conductance increase factor} = Conductance_{(desired)} / Conductance_{(actual)}$ (2-13)

Conductance increase factor = 2 S / 0.5 S = 4 (unitless)

$Conductivity_{(wastewater)} = 1000\ \mu s/cm = Conductance * \text{Cell Constant}$ (2-14)

Multiply by Conductance increase factor →

$\text{Conductivity}_{(\text{desired})} = 1000\ \mu\text{s/cm} * 4 = (\text{Conductance}*4) * \text{Cell Constant}$ (2-15)

$\text{Conductivity}_{(\text{desired})} = 4000\ \mu\text{s/cm}$

$\therefore$ New $\text{Conductance}_{(\text{in test unit})} = 2$ S and R = 0.5 ohm

$P = U^2/R = 32^2/0.5 = 2048$ Watts (2-10)

Thus if the conductivity is raised to 4000 μs/cm the test unit will be able to apply 64 A to the wastewater with a power consumption of 2048 Watts.

Situation B – Increase the Driving Volts

$R_{(\text{actual})} = U / I$ (2-11)

$R_{(\text{actual})} = 32\text{ V} / 16\text{ A} = 2.0$ ohm

$U_{(\text{desired})} = R * I$ -- Desired amperes are 64 A so this is adjusted, resistant remains constant as no salt is add, the transformers are replaced increasing the driving volts allowing the increase in amperes.

$U_{(\text{desired})} = 2.0\text{ ohm} * 64\text{ A}$ → Driving volts adjusted in this scenario

$U_{(\text{desired})} = 2.0\text{ ohm} * 64\text{ A} = 128\text{ V}$

$P = U * I = 128\text{ V} * 64\text{ A} = 8192$ Watts (2-4)

Thus, we see that it is favorable to increase the conductivity over increasing the driving volts as less power is required for identical treatment (i.e. the same current from the electrodes in the cell is applied to the water although in first scenario there is an additional pollutant, salt, which was required to increase the conductivity which prevents discharges to freshwater environments).

Ideally, the equivalency of the relationship could be tested and proven by increasing the driving volts into the system (i.e. replacing the transformer). Without access to additional driving volts the equation (2-4) and ohms law (equation 2-5) will have to be used in conjunction with the known conductivity increase. The experimental error from this extrapolation should be limited to the impacts of the salt on the solution itself and its associated impacts on the flocculation of the solids. Chen et al. (2000) suggested that when amperes are kept constant the actual amounts of salt (NaCl) in the wastewater does not significantly impact the electroflocculation process. Thus, it is assumed that relating the changing conductivities to the equivalent required driving volts increase is a fair assumption for determining the required power for treating the municipal wastewater without salt addition. Other problems associated with this assumption are that the Electrofloc^{PLUS} system designed by AOT may be inadequate to accommodate the additional driving volts that would be required.

2.4.4 Application Issues

2.4.4.1 Bubbles

The bubbles associated with the Electrofloc^{PLUS} system are hydrogen gas (as per equation 2-2) and are entrained within the coagulated solids resulting in their flotation. The bubbles are generated by the electrolysis of water. The water flowing between the cathode and anode is reduced to hydrogen gas at the cathode (Koren and Syversen, 1995). The gas bubbles are essentially the same small size. As the current in the electrolytic cell is raised the gas bubble flux is raised and the separation effect is increased. Although, when the gas bubble concentration is increased the opportunity for two gas bubbles to collide is increased. This process has the impact of lowering the separation effect. The bigger gas bubbles are less effective than smaller gas bubbles as a reduced surface area to volume ratio will occur. Furthermore, gas bubbles have a lower conductivity than the electrolyte, which increases the power consumption (Koren and Syversen, 1995). Thus, as gas bubble concentration is increased the amount of separation is increased as the current is raised up to a particular point, after which the gas bubbles give too large a contribution to the electrolytic resistance and too many of the bubbles begin to coalesce. The amount of separation then slowly declines as the current is raised. Eventually increases in the current will no longer have a significant impact on the amount of separation. Thus, there is an ideal current that should be applied per pass. From experience with this test unit it was found that the more amps applied per pass the better the treatment results. No upper limit has been found. The test unit has been set to a limit of 62 amps and operating at or near this level gives the best performance. When working with primary effluent 100% flotation of flocs was seen with the electrofloc test unit after allowing a short time for flotation.

2.4.4.2 Pre-Ozonation

The effects of the pre-ozonation process in water treatment has been reasonably well documented. However, the use of a pre-ozonation process in wastewater treatment has been reported relatively little. Research has experimentally shown that ozone can improve the coagulation process and improve the removal of organics although the exact mechanisms are still uncertain. This section will review some of the pertinent research in this area to help suggest the possible impacts and mechanisms of the pre-ozonation process with the Electrofloc^{PLUS} system.

A large amount of experimental data has shown that pre-ozonation has an impact on the coagulation/ flocculation process (Grasso and Weber, 1988). The major effects reported when various amounts of ozone are added to raw water in conventional chemical treatment have been summarized by Jekel (1994). These effects include a direct aggregation of particles determined by a shift in the particle size distribution to increased diameters and by changes in turbidity. Another effect found experimentally includes the creation of colloidal or suspended particles from dissolved material as suggested by raised turbidity and increased TOC/DOC-removal afterwards. Articles have shown better particle removal in filtration when using pre-ozonation in conventional chemical treatment allowing decreased additions of coagulants (as much as 50%) and extended filter runs. Improved floc settling rates have been found when using pre-ozonation. Experimental reports have suggested that seasonal benefits of pre-ozonation correspond to when raw waters have elevated algae concentrations. Additionally, it was found that in some cases the removal of dissolved organics might decline when using alum or ferric salts for coagulation after pre-ozonation with larger doses.

The complexity of ozone reactions and source water composition has made mechanistic models difficult to develop that accurately explain the observed events. The work of Jekel (1994) attempted to describe all the coagulation/flocculation mechanisms of pre-ozonation in water and wastewater by reviewing the available reports showing many different processes occurring. Jekel (1994) suggests that several processes are likely responsible and determining these could lead to developing a system to determine an optimum ozone dose for a given application.

Many investigations into the determination of mechanisms responsible are limited by the knowledge about the chemical characteristics of the dissolved organic content (DOC) often being of the fulvic and humic acid type or caused by algae products. Some of the mechanisms discussed include:

a)Ozone may release and/or oxidize metal ions (Fe^{2+}, Fe^{3+}, Mn^{2+}, Al^{3+}) from organometallic complexes, leading to the coagulation action of the hydroxides precipitated.

b)The oxidation of dissolved organic content may lead to carboxylic acids which are precipitated by calcium ions and induce coagulation.

c)The well-documented steric or electrostatic stabilizing effects of natural organics on inorganic particles are reduced or eliminated by pre-ozonation due to desorption from the particle surface.

d)Ozonation at low levels may induce a partial polymerization of dissolved organics forming polyelectrolytes which can act as classical flocculant aids by adsorption and particle bridging.

e)Ozone can cause the lysis and destruction of algae cell walls or of associated organic substances, renedering algae cells to become better coagulatable, filterable or flotable.

f)The loss of CO_2 during ozonation can induce $CaCO_3$ precipitation and particle aggregation.

g)The interactions of dissolved organic substances and the coagulants are influenced by ozone, inducing an improvement or a decline in overall efficiency. Jekel (1994)

Grasso and Weber (1988) conducted a study in an attempt to gain understanding regarding the mechanisms involved in ozone induced particle destabilization. They conducted a series of experiments designed to isolate the responsible mechanisms based on previously proposed mechanisms from earlier research. The results of this work suggested that the mechanism by which ozone induced particle destabilization occurred was polymerization of metastable organics and subsequent adsorption and interparticle bridging or charge neutralization. This research also suggested that nature and chemistry of both particulate matter and the dissolved organic matter play important roles in ozone induced particle destabilization.

2.4.4.3 Power Supply

The design of the power supply to the electrochemical cell is a primary concern when developing an electroflocculation unit. It greatly impacts the variability of the treatment process and should ideally provide consistent continuous power to the electrochemical cells. It also impacts the process optimization as it contributes to the overall efficiency of the test unit. The test unit used in this project utilized a proprietary system from AOT. Little is known about its operation except that it does not seem to effectively provide a consistent current to the same wastewater throughout a run.

2.4.4.4 Conductivity

As discussed earlier the conductivity of the water to be treated impacts the process greatly. As such in areas where the water is to be discharged into the ocean it is favorable to add salt into the wastewater to raise its conductivity or to mix seawater with the wastewater. In areas where this not possible a great deal more driving volts are required in order to have the machine work with the same performance as if mixing with salt water were possible. Using the conductivity data from Table 2-5 it can be seen that by adding 5% of a 53 ms/cm seawater to a 1.1 ms/cm wastewater that the overall of conductivity can be raised to 3.7 ms/cm (i.e. (53 ms/cm * 0.05) + (1.1 ms/cm * 0.95) = 3.7 ms/cm). If the amperes applied to the water was to be kept constant and the resultant treatment were to be kept constant then this conductivity increase would allow for a resultant 3.4 times reduction in the amount of volts (and power) required to drive the system at a given level of amperes applied. If the wastewater had a lower influent conductivity then power reduction would be even more pronounced.

2.4.4.5 Electrochemical Cell Design and Age

The electrochemical cell design is a very important consideration. Pletcher and Wenberg (1992a) discuss cell design in detail. The design will impact power consumption of the electrochemical cell for any wastewater of any conductivity. Well-designed electrochemical cell can greatly improve process efficiency. Designs that promote turbulence (without creating large bubbles) and increase the available surface area of the electrodes are key considerations in the design efficiency. The inter electrode is also an important consideration in cell efficiency.

The age of the electrochemical cell also impacts process performance. Aging cells develop passivation layers that cause the current (in amperes) to decrease given a same wastewater with the same conductivity and the same amount of driving volts (Donini et al., 1994). Also the dissolution of the aluminum into the water will gradually cause changes in the electrochemical cell such as corrosion pits (Chen et al. 2000). These changes will impact the bubble forming process (i.e. gradually larger bubbles are formed) and the dissolution performance of the aluminum anode.

2.4.5 Process Temperature Impacts

The increase in the water temperature caused by the direct exposure of water to an electric current in an enclosed system (assuming no thermal losses or gains from outside the system) can be determined using joules law. This concept is important as it can determine the optimal temperature change under ideal conditions. If the optimal change does not pose a significant thermal threat to the ecology of the receiving water as discussed in Table 2-3 then this factor, as ecological issue, can be ignored (of course it still may be issue from the operational and process optimization standpoint). If optimal temperature increase does suggest a potential large scale thermal problem then the actual temperature change should be examined in greater detail.

A calorie is a measure of energy and by definition is the power required to raise to 1 gram of water 1 degree Celsius. A joule is another unit of energy and 1 Calorie = 4.1868 Joules. These relationships in can deducted:

Calorie = mass of water in grams x temp rise in °C (2-16)

Joule = watts-seconds = voltage x current x time in seconds = 4.187 calories (2-17)

Energy released (Joules) = mass of water x temp rise in °C x 4.187 (2-18)

Energy released (Joules) = voltage x current x time in seconds (2-19)

Therefore:

Voltage x current x time in seconds = Mass of water x temp rise in °C x 4.187 (2-20)

Rearranged:

$$\text{Temp rise in }^{\circ}\text{C} = \frac{\text{voltage x current x time in seconds}}{\text{mass of water (grams) x 4.187}}$$

For example if the test unit pumped 1 litre through the electrode every 1.46 seconds and the voltage of the unit is 32 V and the maximum current is 62 amperes then the following equation will show the expected maximum temperature increase of the water in a ideal system with no outside thermal losses/gains.

$$\text{Temp rise in °C} = \frac{32\text{ V} \times 62\text{ A} \times 1.46\text{ s}}{1000\text{ g} \times 4.187} = 0.7\text{°C}$$

Now if the water is run through the test unit seven times at 62A then the total maximum increase in temperature would be expected to be 5 °C. Thermal changes from other parts of the system (i.e. from the ozone addition are not included in this value).

2.5 Key Reports and Patents

The use of electrochemical processes for wastewater treatment has been discussed in the literature since the 1880's (Vik et al., 1984). Eugene Hermite received two British and French patents in 1887 that summarized a technique of treating sewage by combining the sewage with a portion of seawater and electrolyzing. This patent was utilized in London at a treatment facility that operated from 1889 to 1899. The first patent in the United States was to J.T. Harris who received a patent in 1909 (U.S. patent, 1909) for a wastewater purification technique using electrolysis. Treatment plants using electrolysis were in operation in Oklahoma City and Santa Monica, California as early as 1911 but were abandoned by 1930 due to high operational costs (Collier, 1912). Relatively little research was conducted from that time until the 60's when the Russians began significant research in the area including the creation and operation of full scale plants. Because much of the literature from the Russian experience has yet to be translated specific details regarding the scale and performance is unclear (Oloman, 1996). It would be very valuable for a bilingual environmental engineer to do a literature review summarizing the Russian results (i.e. Kharchenko et al., (1985), Pryhegorlinski, (1987), Sleptsov et al. (1987), Zhul'kov, (1978) Zolotukhin, (1989) as well as many others).

Recently the use of electrochemical methods to treat wastewater has seen increasing interest in western countries and this research has allowed for the improved performances permitting the commercialization of the electrochemical technology in primarily the industrial wastewater treatment area. Commercially available electrochemical treatment systems include the Purifier, (Koren and Syversen, 1995) Chemelec, Retec, en Viro-cell and the Electrocell (Pletcher and Weinberg, 1992b). Patents concerning electroflocculation technology include Valanti (1985) and Cole (1989). Additionally, newly developed electrochemical water and wastewater treatment technology was found to be available from a number of companies at their Internet sites. Electroflocculation treatment systems need to be carefully set-up on site and the power supplies and cell configuration need to be adjusted to function with different wastewaters and flow regimes.

Recent articles reporting the principles and practice of electroflocculation include articles by Barkley et al. (1993), Mills (2000), Koren and Syversen (1995), and Saur et al.(1996). Design of electrochemical cells for wastewater treatment is discussed by Pletcher and Wienberg (1992a). Operational costs of the process has been discussed by Donini et al. (1994). Recent research reported discussing the use of an electrocoagulation and floatation process for treatment of municipal wastewater includes a report by Pouet and Grasmick (1995).

3 Methodology

This section will discuss the experimental protocols used for the data collection from the test unit.

3.1 Approach

This project will take a cautious and critical look at all the acquired evidence/results on the systems performance to provide unbiased and independent results on the effectiveness of the Electrofloc^{PLUS} demonstration system. The technology is relatively new and unproven and as such requires more study to be put forward to the consulting industry and regulatory agencies. This cautious approach is important as environmental concerns and problems are becoming a major issue to the public and policy developers. New ideas and technology are required to meet the environmental standards and objectives most efficiently. Objective and critical research is required to ensure that new technology is effective as well as efficient. This approach will ensure that the disseminated results to be discussed in section 4 will accurately and fairly portray the effectiveness of the Electrofloc^{PLUS} system allowing it to be put forward for use in appropriate municipal wastewater situations. Thus, allowing for a safe and clean environment for all to enjoy. As such the performance parameters examined included pH, 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), total phosphorus (TP), ammonia, total nitrogen, nitrates, nitrites and fecal coliforms. Additionally, the reduction of surrogate bacterial spores, *Bacillus subtilis*, will be used for evaluating potential protozoan reduction will be examined in concert with challenge to determine the reduction/kill of the pathogens *Cryptosporidium spp.*

3.2 Experimental Design

The experimentation can be divided into essentially three phases and a preliminary phase. The preliminary phase involved basic testing of the unit in order to learn basic operational procedures of the test unit (i.e. getting the unit working). Often during this phase the test runs had limited success (creating effluent no clearer than initial primary effluent) and were not analyzed or the analysis was limited to a few TSS samples. Much of the most valuable information from this phase came from qualitative observations and qualitative data interpretation as opposed to statistically significant quantitative data and inferences.

The first phase served to develop consistent sampling protocols and to determine optimal wastewater conductivity levels for treatment and to improve the replication of the same test runs. Analytical procedures were also further developed to improve accuracy. Essentially an iterative process was used to make corrections and improve test unit performance and sampling/testing techniques. The conductivity-amps applied relationship was defined for the unit during this phase so that operational costs could be estimated for all samples.

The second phase was used to make determinations of the test unit's performance using consistent and effective protocols. Tests were performed to confirm suspicions from the data from the preliminary and first phase. A factorial design was utilized to determine the main effects and interactions between different input components including treatment level (amount of amps applied), ozone dose and electrode material. Based on the results of the factorial design multiple tests under the optimal conditions were performed with changes only in the collected raw primary effluent gave additional confidence in the systems performance abilities and the resulting treatment level that could be expected given the inputs

The third phase involved the final testing of the unit to further determine its potential for microbiologic reduction specifically the protozoan oocyst *Cryptosporidium parvum.*

The specific results and what can be concluded from them for each experimental phase will be discussed as part of the results/discussion section. The rational for the use of the factorial design will be discussed here.

3.2.1 Factorial Design Discussion

An experimental design technique suggested for many Environmental Engineering applications related to water treatment is that of factorial design. Additionally, Heitz and Kreysa (1986) suggest that this technique is also appropriate for many electrochemical applications to give a basic summary on its performance under different conditions. Detailed descriptions on the use of factorial design can be found in Box et al. (1978). The advantages of using this technique for this project includes being able to investigate the different factors involved in the full process with fewer experimental runs and the main and interaction effects can be identified and quantified allowing cause and effect relationships to be established.

The variables used as part of the factorial design (electrode material, ozone dose, amperes applied) were difficult to assess in terms of there interactions with the treatment level and the resultant performance so these were selected to help determine there impact on system performance especially in terms of there interrelationships (as a factorial design can determine both additive relationships as well as synergistic relationships). This is in contrast to the one variable at a time approach which determines changes in the performance parameters as one experimental condition is changed but fails to establish what might happen if variables are changed not individually but together (Box et al. 1978).

Unfortunately, there are also some limitations in the use of the factorial design under the conditions present in this study as well as limitations in how the resultant data are interpreted. The conditions of the raw primary effluent are changing and as such this control parameter (wastewater characteristics) was changing and thus making the final results less meaningful (i.e. are differences in results due to changing wastewater parameters or are they due the changing the treatment conditions). This was mitigated by the use of true triplicates meaning the process was repeated start to finish three times with different sample. Also, factorial design requires consistent input conditions (i.e. ozone dose, electrode type and amperes applied) across the different test runs while only varying the specific parameters in question. With the test unit used this made analysis difficult as the amperes applied was somewhat variable between test runs even when all conditions were kept the same. Therefore, as a surrogate to amperes applied the number of passes through the test unit was used as this parameter could be kept consistent and should approximate the amperes applied.

3.3 Test Unit Operation

3.3.1 Initial Set-up

The test unit used was the Electrofloc^{PLUS} wastewater treatment demonstration system. The unit contains the following components:

a) electrical enclosure;
b) filter (not used for this project);
c) process tank;
d) pump;
e) ozone generator;
f) air dryer;
g) venturi injector;
h) one AOT Inc. RPS-8C cell excitation module; and
i) two AOT Inc. EFC cells.

This compact mobile system includes an enclosed layout of electrochemical cells, ozone generator, mixing tank, pump, valves and filter. The system was originally designed for batch tests only and was not designed to accommodate a continuous flow regime. However, the unit was modified for single pass treatment. This demonstration system was designed by AOT Inc. primarily to define the treatment capabilities of the company's proprietary electrocoagulation/ flocculation/ oxidation processes (AOT, 1999). This demonstration unit is fairly simply to start requiring only a suitable electrical source. The system was enclosed within a solid metal frame with a footprint of 1.370 m long by 0.96 m wide and 0.96 m high. The system can be seen in the photograph in Figure 3-1.

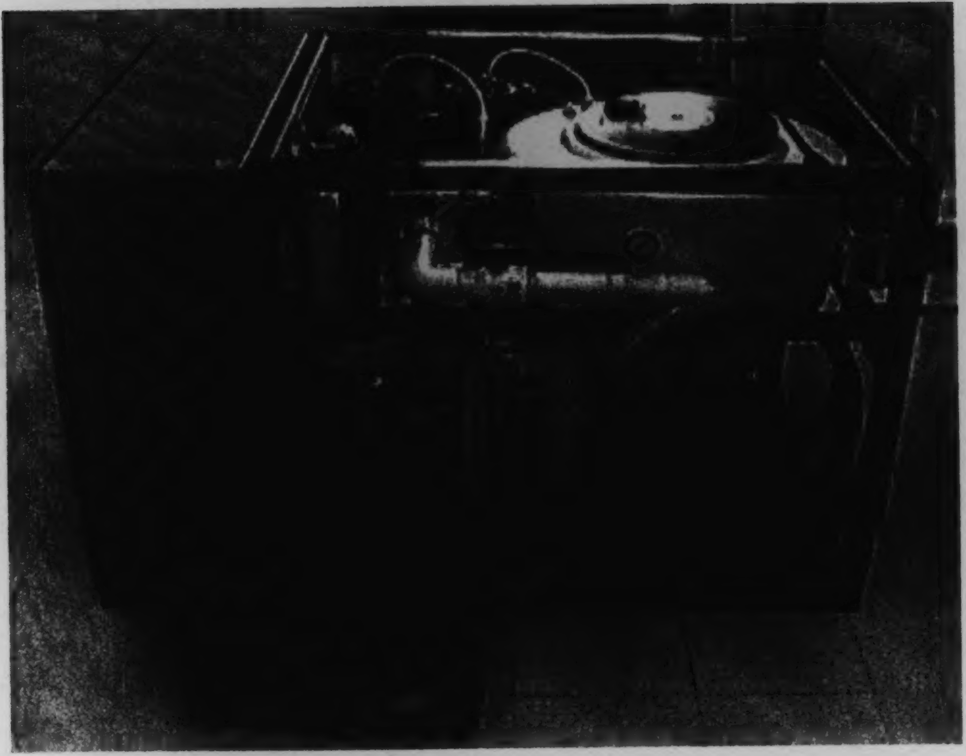

Figure 3-1 Test Unit

The Electrofloc^{PLUS} system is in a patent pending timeline and therefore the electrochemical cells and the electronics are considered proprietary. Each electrochemical cell has been sealed by AOT with a small metal tab, which was not to be tampered with, or broken. Therefore, inspection of the cells was not possible.

3.3.2 Test Unit Treatment Processes

Figure 3-2 gives a schematic of the process configuration occurring during a typical test run.

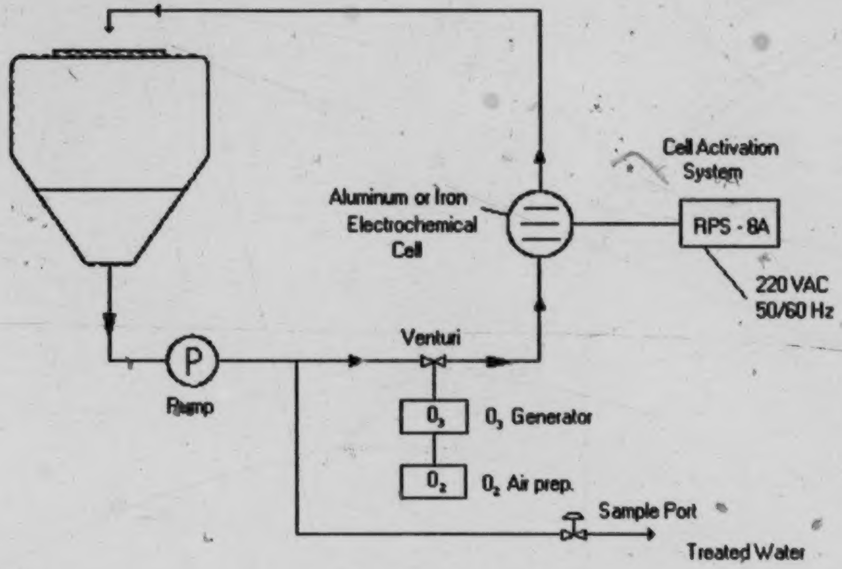

Figure 3-2 Test Unit Process Diagram

Initially, ozone, was introduced to the wastewater just before the water was sent to the electrochemical cell. This step was thought to improve the coagulation and precipitation, through the pre-ozonation processes discussed in section 2.4.4.2, occurring in the electrochemical cells. The electrochemical cell is comprised of non-conductive piping equipped with rectilinearly shaped, metal electrodes that sustain an electrical current between them during operation. It is suggested (AOT - flyer, 1999) that applying an alternating current electric field to the electrodes causes the dissolution of the electrodes or suspended metal media and formation of polymeric hydroxide species which start the neutralization of electrostatic charges on suspended solids making possible their coagulation. The coagulation process starts within the elctrochemical cell and continues after discharge from the cell. The literature suggests and AOT claims that the resulting floc from this process is more shear resistant and readily filterable while being less hydrous (Barkley et al. 1993). This project has found qualitative evidence that agrees with their assessment. It appears that the flocs stay fully intact even after being run through a blender for up to two minutes.

Applying an electrical field to the water causes electrolysis of the water medium and the creation of hydrogen gas bubbles. This gas attaches to the floc resulting in a quick flotation of the solids. The process has been referred to in the literature as electroflotation.

3.3.3 Power Supply (for the Test Unit)

The test unit requires a significant amount of energy to function. An electrical source with sufficient voltage and capacity was required. The demonstration system required 220 VAC, 60Hz, 60Amps capacity – single phase, alternatively, the test unit can operate off two legs of a three-phase supply – i.e. 208 VAC 60Hz 60Amps capacity (AOT, 1999). The energy source must be sinusoidal which eliminates most affordable generators from working efficiently with the system. This energy source is used to power the pump, the ozone generator, and the internal power supply.

3.3.4 Maintenance

The test unit is designed in such a way that limited maintenance is required for proper functioning. The process tank is washed with a damp paper towel and rinsed after each test run to prevent cross-contamination between the different test runs. Clean clear water is circulated through the cells at least 10 times to rinse the unit.

3.3.5 Performance

The basic component parts of the test unit worked for the most part. The outside metal structure was sound and kept the unit well protected. The ozone generator worked acceptably for the entire project, as did the ampere meter to measure the power applied. The pump worked every time but once and required some manipulation to get re-started. The plumbing of the test unit proved to be waterproof as no leaks within the system were observed during the course of the project.

In regards to treatment performance limited information was available about the test unit prior to the study especially in regards to municipal wastewater and therefore no benchmark existed to evaluate this test unit in comparison to other Electrofloc^{PLUS} test units. During the course of this project AOT has been operating a pilot scale plant in Ladysmith, British Colombia. However, the unit used for the pilot plant differs significantly from the test unit used here. The pilot system tested in Ladysmith was not only significantly scaled-up but also had considerably different electrochemical cells. The test unit used in this project utilized a plate system while the electrochemical cells in Ladysmith used a pellet system. Further discussion in regards to the specifics on the electrochemical cells in the test unit is not possible as these are considered proprietary and as such the specifics are unknown. Also, the power supplies between the two systems may differ. These are proprietary and little is known regarding their functioning. Therefore, little is known about the two key components of the electroflocculation systems. The studies purpose was to define the performance of the test unit given the known power inputs. These components (power supply and electrochemical cells) on the Electrofloc^{PLUS} test unit operated as intended throughout the project with the possible exception of gradually declining performance of the electrochemical cells likely due to the consumption of the electrode materials and/or the development of passivation layers on the cells. Based on the scientific literature this decline is expected. Developing proper protocols and practice with the system improved treatment performance and allowed these components to function to their full potential. The test unit could benefit from better user configurability and diagnostic tools (such as variable flow rate control and a data logger for the applied amperes) to ensure proper functioning of all components.

3.3.6 Test Unit Modifications

The test unit design was modified in order to obtain better scientific data related to its performance. These modifications included adjusting the flow scheme to allow for the wastewater to be tested in a single pass and then this process could be repeated to see cumulative performance (i.e. use of multiple passes simulating a series system). The wastewater would be put in the process tank and run through the system one time and the appropriate data for that pass would be recorded. The water would then be stored in the holding tank. This water would then be returned to the process tank and the procedure repeated. Thus, allowing for accurate measurements of the cumulative impacts of the electroflocculation process. (e.g. wastewater treatment after one pass with a total of 60 amps applied, two passes with a total of 120 amps applied, five passes with a total of 300 amps applied etc). Sample was always collected from a sample port directly into a "jar test" container thus allowing consistent flotation to occur between passes and runs. This method allowed for accurate readings of amperes applied as well as ozone addition and water flow rate. Also, it allowed the water being treated to be monitored precisely for it's given amperes applied. The following figure shows the set-up of the modified unit.

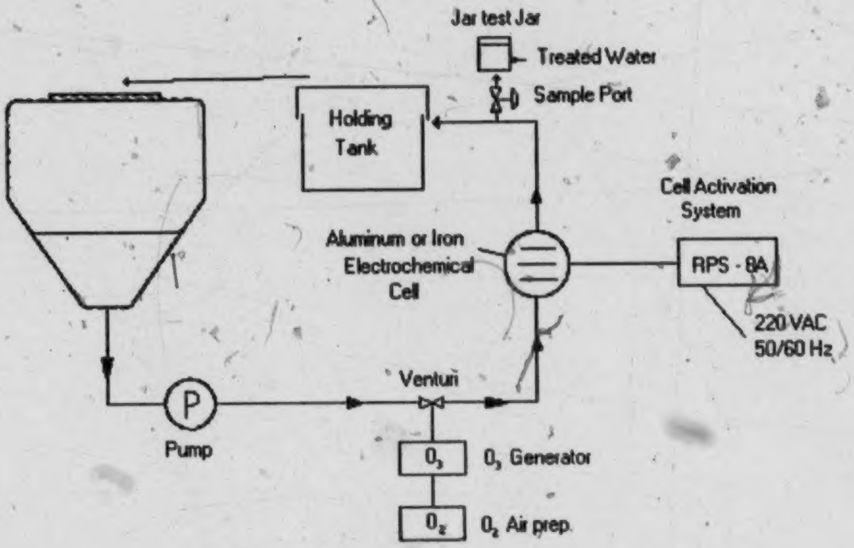

Figure 3-3 Test Unit after Modifications

3.4 Testing Protocols

3.4.1 Sample Collection

Each sample was collected at the Gold Bar Wastewater Treatment Plant run by the City of Edmonton. The facility is located on the south bank of the North Saskachewan River at 10977-50 Street, Edmonton, Alberta, Canada. Figure 3-4 shows a picture of the Gold Bar facility.

Figure 3-4 Gold Bar Wastewater Treatment Facility

Typically sample collection was started upon arrival at Gold Bar at around 7:00 to 7:30 and finished at around 8:00 to 8:30. The primary effluent sample was taken directly from the primary effluent channel after the weir at a butterfly valve via a rope and bucket Then the sample was poured into the sample containers with a funnel. Depending on the number of tests and the purpose of the tests, sample containers were usually filled for a total of approximately 65 L of sample. This sample was immediately taken via automobile to the U of A, Environmental Engineering Building to be run through the electrochemical test unit. This transfer time to drive to the Environmental Engineering Building and unloading the sample containers, to starting the treatment process typically took 60 minutes to 75 minutes. The sample collection site is shown in Figure 3-5.

Figure 3-5 Sample Collection Site with Sampling Bucket

3.4.2 Test Run Volume

The size of the sample used for a run was typically 30 litres as this was the most sample that could be conveniently used. This, however, was variable (primarily during early exploratory test runs) depending on the purpose of the test run and the amount of sample required to be taken during the test run. Samples of 34 litres were tried a few times but the additional load into the holding tank made recycling difficult so 30 litres was typically used. The actual amount of sample however is not overly important while running the test unit in single pass mode as the sample gets treated equally whether 4 L or 400 L run through the test unit. The primary advantage of using larger samples is that the experimental error from delays at start-up and the residual water at the end of the test run are reduced as they are spread out over a greater sample volume.

When running the test unit without modifications a 15 litre sample was used as was suggested by AOT (AOT, 1999).

3.4.3 Operational Notes

The machine was very difficult to get operating; as the manual and help received from my visit to AOT. was inadequate for operating this unit which was originally designed for blood water (not municipal wastes) (Lambert, 2001). The manual also contained some inaccuracies that caused a great deal of confusion (i.e. generally requires operating currents of under 20 amps). First the test unit was operated unmodified as per the manual. The following list indicates the steps required in the manual:

-Check valve positions

-Turn on breakers

-Add 15 litres of clean water into process tank

-Check pump pressure to ensure pressure value was in excess of 30 PSI

-Check downstream pressure to ensure it is half of upstream pressure (to ensure pressure differential for venturi operation)

-Check balance discharge tubes are flowing gas/liquid mixture

-Check balance barometer in the ozone circuit is indicating venturi section

-Drain clean sample and add wastewater sample

-Run for several minutes and take sample to check for flocking

The list of these procedures did not result in effective wastewater treatment. Therefore, an iterative process was used in order to develop an effective operating procedure. This iterative process determined much about the operation of the unit. However, the variability in the machines power supply of amps to the electrochemical cell made the process difficult. It was not clear if an alteration in the testing procedure was the cause of fewer amperes being supplied or if it was random variability in the test units functioning. The following section discusses some of the steps that were discovered to reduce the variability. Eventually the machine was modified as discussed above to allow for greater knowledge about of the precise addition of current to the wastewater. The iterative process was once again used to get the test unit functioning so that similar levels of reductions between the batch runs and the single pass runs were achieved.

The iterative process also allowed for the improvement of sampling techniques from the test unit. As an example of how the iterative process was used in the project the following experience will be related. First an Imhoff cone was used for collecting the electroflocculated water sample and a peristaltic pump with a plastic tube was used to extract the separated treated water sample from the middle of the Imhoff cone after 30 minutes to allow all the separated floc to be floated to the surface by the hydrogen bubbles. It was noticed that while putting the tube into the cone that floc was pushed down and was subsequently pumped into the treated sample jar for analysis. To prevent this the next step was to collect the sample with the tube placed in the Imhoff before adding the sample this resulted in less floc being pushed down but the currents from the peristaltic pump still pulled down the floc. The pumping process was also time consuming. The next step was to try a different idea all together being the use of a jar test container and collect directly from the port in the jar. The method worked quicker and did not disturb the floated flocs. In a comparative test (for TSS) it was found that this method allowed for best removal. The next problem noticed in the sample collection procedure was variability in the floating properties amongst similar samples. The sample was being collected from the holding tank at this time and thus was stirred when collected to get a representative sample. This stirring caused the inconsistent loss of the hydrogen bubbles and effectively created inconsistent flotation. To prevent this the sample was collected directly into the jar test container from the test unit therefore no stirring of the sample was required. After this step was taken the flotation characteristics between sample runs became much more constant.

Unless otherwise noted the following testing protocols were used for the testing and results discussed in this document:

-sample collected morning of test run day;

-test machine "warmed up" by running salted tap water (tap water raised to conductivity approximately the same as the wastewater to be run through the system) until the expected amperes are achieved, the machine is also checked to ensure it is working properly (i.e. ozone being produced, flow was normal, etc.);

-test machine filled with sample to selected volume (usually 30 litre) from sample container and stirred;

-small sample of wastewater taken and the temperature and conductivity tested and recorded;

-selected salt amount was added to the sample and recorded;

-wastewater sample is taken for analysis;

-wastewater run through machine with the ozone and power supply on and sent into the holding tank;

-if sample was to be taken during that pass it was taken directly from sample port into the jar test container while the machine is running;

-after the run notes were taken regarding the pass including the amperes applied and if they stayed consistent (if not the time the amperes spent at each level was recorded) , the ozone flow, approximate residual left in tank, if the breakers needed resetting, time sample taken, and other miscellaneous points regarding the run were recorded;

-the wastewater was moved from the holding tank bank into the process tank and the amount of sample remaining was recorded (i.e. less two litres if jar test sample was taken);

-the process was started again until the desired number of passes has been obtained (usually 11 or an approximate cumulative amperes of 625 for 11 passes * 57 amps/pass);

-if two runs were to be done the machine was rinsed and the process is repeated except for the "warm-up" step not done before the second run; the machine is just rinsed thoroughly with tap water raised to a conductivity similar to the conductivity expected for the test run to be performed;

-at one hour of flotation for each sample collected the separated water was drawn from the jar test container into bottles for testing;

-the samples were appropriately stored depending on what they were to be tested for (i.e. acidify with sulfuric acid and refrigerate etc.);

-the machine was then thoroughly rinsed with clean water and the process tank was cleaned with a paper towel;

-the machine was turned off;

-Clean up including rinsing and washing of "Jar test" containers to prevent cross contamination with future runs

3.4.3.1 Techniques to Reduce Ampere Applied Variability

The machine operation was highly variable especially in regards to the amperes supplied to the wastewater thus resulting in variable system performance. Complications with power supplies and ineffective performance with different real wastewaters compared to simulated wastewaters in the lab is commonly described as a shortcoming of any electroflocculation system. After recognizing this problem with the Electrfloc^{PLUS} demonstration test unit steps were taken to prevent the variability.

Three main operating procedures were introduced to reduce the variability. First the test unit was "warmed-up" by running a number of passes with salted tap water (with the salt added to approximately the same concentration as the subsequent test run). This was done until 60 amperes were measured on the ampere monitor for a minimum of two passes through the system (if the conductivity was expected to be sufficient to allow this many amperes). Second the machine was always stopped just before the last bit of water was draining from the tank. This prevented the pump from getting large air bubbles into the system. This procedure causes a small residual to be left in the process tank from previous passes. This residual was consistently quite small because great care was always taken to ensure that the pump and machine was not shut down until the last possible moment. To test how much residual was left, a peristaltic pump was used to suck up the residual into a measuring beaker that showed after a pass between 1 to 4 litres may be present as a residual. Usually, the machine could be operated to keep the residual around 1 to 2 litres of which some may have in fact entered the electrochemical cell and is simply "draining" back to the tank. This unavoidable residual would account for a small experimental error causing the removal rates discovered to be conservative (i.e. actual removal is slightly better than stated results). Third, the circular swirling of water in the process tank caused an air tube to reach the bottom of the tank again causing air bubbles to get into the pump that seemed to increase variability in the power supply (i.e. air in the water stream would increase electrical resistance of the wastewater). Simply stirring the water gently counter to the direction of swirling prevented this condition from occurring. Also, the gentle stirring also prevented the flotation process from occurring inside the tank from previous passes and allows a more homogenous sample to be subject to the electrochemical cell during each pass through the unit.

Another, less common step taken to prevent variability of the results included resetting the breaker when amperes applied to system were not as high as they should be. Often when operating the test unit the power supply would, for no apparent reason, instantly give significantly less amperes than at other times during a test run (i.e changing from 60A to 20A). This process was common and would usually "recover" without altering the treatment process but on rare occasions the test unit seemed unable to re-achieve the maximum amperes that it had previously been producing. If the unit seemed to be operating at the lower ampere level for a long time period without "naturally" (i.e. without manual intervention) being able to recover the flow would be stopped and the breaker reset After resetting the breaker the machine would usually go back up to the expected maximum amperes. Stopping the flow and resetting the breaker was only conducted if it seemed clear that the unit would not recover. This process was avoided as stopping the flow created "start-up" issues that would not be present on other passes. When possible the breaker was reset at the end of pass to prevent adding additional start-up issues. When the unit was reset it was noted alongside the amperes applied data. It seemed that for certain wastewater samples (i.e. 0314R1 and 0314R2) this would happen more frequently than for other samples. Also, this problem was more common when using the iron electrode and only once was this method required when using the aluminum electrode. Overall this method was not required very frequently.

Unrefereed literature and discussion on electroflocculation suggests that variability in the operation of any given test unit is common in situations where one is applying electrochemical cells and power supplies developed using one type of wastewater to a different waste stream. The test unit supplied for this project was originally developed for blood water (Lambert, 2001) so it should be no surprise that its performance is variable with municipal wastewater.

Despite that above mentioned protocols to prevent variability, variations as large as 10 to 64 A could be commonly found both within individual passes through the system and between different runs. Qualitative records were kept to give an idea of the frequency and significance of the variability of the power supplied. These results will be discussed in section 4.3.1.

3.5 Ozone Determination

To check the ozone addition from the venturi injector a lot of problems were experienced and consumed a great deal of time with limited success. Attempts to hook up an ozone monitor to the test found limited success. The ozone monitor when attached to the machine caused the venturi injector to short circuit and water fell back into the ozone line causing the ozone flow to be continually disrupted until it reached the water trap then the short circuit process started again. Other problems while attempting to monitor the ozone were experienced. Adding DI water to the test unit and taking direct ozone concentration measurements by using direct UV absorbance also found limited success as the readings were not very accurate as the ozone demand of the DI water (and any unrinsed material that might be left over in the system) and the loss of ozone to the air before the measurement caused these readings to underestimate (perhaps by about 30%) the ozone added. Also, any debris left in the system that was "picked-up" by the DI water would cause background interference. The test was performed simply by taking a reference DI water blank and measuring the absorbance at 260 nm on the Ultrospec 2000 UV/visible spectrophotometer then measuring the absorbance at 260 nm of the DI water run through the test unit immediately. The following equation can be used to calculate ozone concentration present.

$$C = [A_{260,\,\text{sample}} - A_{260,\,\text{reference}}] \times 14.45 \qquad (3\text{-}1)$$

The relative ease of this test allowed its use on a few occasions simply to ensure that the ozone generator was working properly. This test has measured the ozone concentration in the DI water was determined to be around 0.6 to 0.75 mg/L. Another indicator that the ozone generator was working included a simple qualitative assessment that there was an ozone scent in the air during the test unit warm-up. If it could not be smelt (perhaps due to a cold etc.) the direct measure test was used to ensure ozone was present.

The most accurate method to measure the ozone applied by the test unit is to put a known quantity of Indigo solution into the machine after the machine has been thoroughly rinsed and run it through the test unit with the ozone off to satisfy the ozone addition from residual in the test unit. Take a sample of this solution and measure the absorbance at 600 nm to use as a blank and return the remainder to the test unit and run it with ozone production. Then measure the absorbance at 600 nm of the indigo solution after it has been run through the machine. To measure absorbance the Ultrospec 2000 UV/visible spectrophotometer was used. The change in absorbance was then related to the exact amount of ozone applied to the solution as per the following equation.

$$C = \frac{(A_{600,\,blank} - A_{600,\,sample}) \bullet V_{total}}{f \bullet V_{sample}} \qquad (3\text{-}2)$$

Where $A_{600,blank}$ and $A_{600,sample}$ are the absorbances at 600 nm in a 10 mm cell for the blank and sample. The V sample and V total are the volumes of the original sample and the total volume of sample and indigo reagent in mL. The f value is the sensitivity coefficient is defined as 0.42 $Lmg^{-1}cm^{-1}$ (Craik, 2001).

This entire process was repeated three times for each batch of Indigo solution made while taking duplicate measures for each pass through the system. This determination was repeated three times during the course of phase 2 of the experimentation, one determination was done near to the beginning of the testing while two test were performed near to the end of this testing phase.

The indigo solution creation and absorbance readings for the determination of ozone dose were performed according to the modified "standard method" (APHA, 1998) used by Craik (2001).

3.6 Flow Rate Analysis

Flow rates were determined by simply measuring the length of time required to drain a specific volume of sample (often 7.6 litres (2 gallons). This test was run intermittently on sample treatment days and also during the ozone dose tests. This was done to ensure a consistent flow rate throughout all the testing.

3.7 Treated Sample Collection

Treated sample was collected into jar test containers and given approximately 60 minutes for the flotation process to occur (comparative tests suggested that only 15 minutes or even less was required but additional time did not result in changes to the separation level for the parameters tested). The sample was then released from the jar test sample port into a bottle appropriate in size and material for the analysis to be conducted. For a blended sample 500 mL was collected into a blender container and the sample was blended using a Sunbeam™ osterizer blender. The mixed sample was then transferred to the appropriate bottle. Figure 3-6 shows separated, collected, and preserved samples used for a phosphorus analysis with the exception of the bottle on the far right which is a DI water blank taken for comparison. From left to right the samples include the original PE, 1 pass through the test unit, 3 passes, 5 passes, 7 passes, 11 passes and the DI water blank.

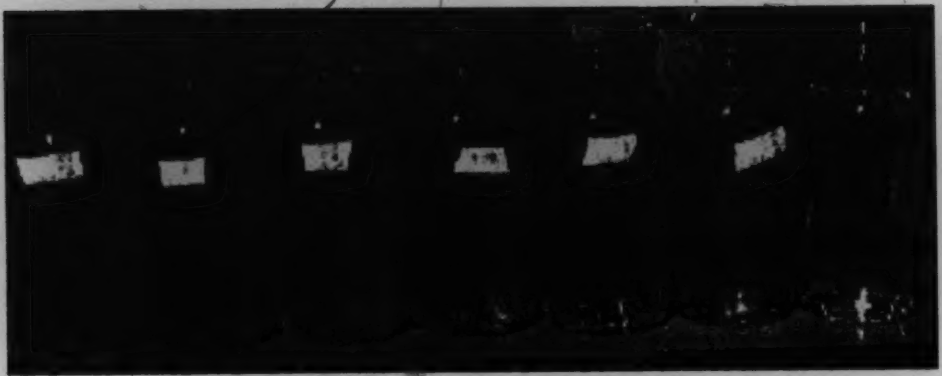

Figure 3-6 Collected Samples at Various Levels of Treatment

3.8 Water Quality Parameter Analysis

The water quality parameters were analyzed according to Standard Methods (APHA, 1998). This section discusses these methods, their theories, highlight and defend the choices made when Standard Methods offers a multiple options for executing a test for a particular parameter (or for multiple choices within a particular test) and discuss any deviations/omissions used for the analyses used. Table 3-1 outlines the Standard Methods number and name (APHA, 1998) that were used for each test (in all cases the introduction to each method and appropriate cross references found in Standard Methods were also used to determine storage requirements and other considerations for the test). When using laboratory equipment as part of a "Standard Method" the equipment was used according to the operational manual in such a way that it complied with the standard procedure.

Table 3-1 Standard Method Test Numbers Used for Project

Parameter Tested	Standard Method Test Number Used
TSS	2540 D.
COD	5220 D.
TP	4500-P (B.5., E.(Manual), F. (In-Line))
TKN	4500-N_{org} B.
Ammonia	4500-NH_3 B., E.
Nitrate + Nitrite	4500-NO_3^- F.
BOD_5	5210 B., 4500-O C. (Winkler), G. (membrane electrode)
Metals	3120 B. , 3030 E.
Fecal Coliforms	9222 D.
Conductivity	2510 B.
pH	4500-H+ B.

3.8.1 TSS General Considerations

Wastewater's chemical, physical, and biological characteristics are determined by the various types and amounts of dissolved substances and particulate matter present. In this context "solids" refer to "matter suspended or dissolved in water or wastewater" (APHA, 1998). High levels of suspended solids tend to make water aesthetically unpleasing and release of suspended solids into the environment also has ecological considerations as previously reported in Table 2-3. Gravimetric methods are often used to determine suspended solids and is "empirical in character and relatively simple to perform" (Sawyer et al., 1994). The information that can be obtained through this relatively simply procedure makes it an important environmental engineering tool for both data exploration and design purposes as suspended solids are a key indicator of the strength of domestic waste.

For this project suspended solids played a key role in the early exploratory stages in getting the test unit operating correctly as it showed the approximate process efficiency for each run. Often this was the only test performed at the early stage. The information from the TSS was invaluable in the development of the operational procedures used for the test unit as well as for experimental design of the testing scheme. As such over 900 filters were used during the course of this project. Additionally, the suspended solids content is an important parameter on its own merits and from a stream pollution control perspective it is as important as BOD (Sawyer et al., 1994).

3.8.1.1 TSS Procedure

The procedure used was based on the procedure outlined in the "Standard Methods for the Examination of Water and Wastewater" (APHA, 1998). This section will outline the procedure used and highlight any deviations from Standard Methods. First gooch crucibles were washed, rinsed and a Whatman Glass Microfibre 934-AH glass fibre filter; 24 mm diameter with a 2 μm nominal pore size were added using forceps. The crucibles and filters were then placed in the Fischer Scientific Isotemp oven at 104 °C for 1 hour and then stored in the desiccators until use usually later that day or on the following day. Prior to filtering the initial weight of each Gooch crucibles was recorded using the Mettler AE 166 analytical balance. The weights were recorded to the nearest 0.1 mg. Using tongs the gooch crucible was placed on a vacuum filtration apparatus and reagent grade water was added to seat the filter. Sample was then filtered through the Gooch crucible and the filtrate was discarded. The volume of sample filtered was as much as could be filtered in reasonable amount of time without the filter becoming completely clogged in order to reduce the errors caused by small weighing inconsistencies. Thus, usually 50 mL of sample was filtered for raw sample and poorly treated sample (generally samples taken after 5 or less passes through the test unit or other treated samples that for whatever reason was not well separated after treatment). Occasionally, when Goldbar WWTP primary effluent samples were concentrated less sample could be filtered. Effectively treated samples could often have much higher volumes being filtered and as high as 100 mL was used. After the filtration process the filter was rinsed with reagent grade water (roughly 5 mL) and placed in the oven. The crucible was then dried at 103 to105 °C for 1 hour and then allowed to cool in the desiccators for 1 hour prior to weighing. The crucibles were then weighed again on the balance and the difference in weight was used to determine the total suspended solids as per the following equation.

Mg total suspended solids/L = (A-B) x 1000 (mL/L) / (sample volume, mL) (3-3)

Where:

A = weight of crucible and filter + dried residue, mg

B = weight of crucible and filter, mg

For each set of analyses triplicate reagent water blanks were used to ensure to effectiveness of the test and the cleanliness of the reagent water. Typically the analyses of the raw sample and blanks were done in triplicate while the treated samples were measured in duplicate. Bentonite standards were also prepared and run periodically to ensure the efficiency and appropriate recovery of the method. Due to the nature of the samples they were usually tested the evening that they were run through test unit. Occasionally, the samples were stored overnight at 4 °C and tested early the following morning the day after being run through the test unit (no chemicals were applied for preservation).

3.8.1.2 TSS Analytical Quality Assessment

For all tests blanks were run along with the experiment to ensure the cleanliness of the crucibles, cleanliness of the blank water, and the cleanliness of the pipettes used. Normally a minimum of three blanks were run one for each set of crucibles tested, one was done at the beginning of the procedure one in the middle and one at the end. For all TSS tests performed from March 20, 2001 until the end, the sum of the weight change for all blank crucibles totaled -0.0002 grams with an average change of 0.0000 grams over the 31 blanks tested. This demonstrates that no bias was introduced from the testing method.

The average difference and standard deviation of differences quoted in Standard Methods (APHA, 1992) suggests that values 3.2 mg/L and 2.8 mg/L were obtained in duplicate analysis of 50 samples of water and wastewater respectively. For the 46 samples measured in duplicate from TSS experiments performed July 11, 13, 17 and 19 average difference between duplicates was 3.4 mg/L while the standard deviation of differences was 3.0 mg/L which is in line with what was reported by Standard Methods. It is also is important to note that the raw Goldbar WWTP PE was typically measured in triplicate for superior accuracy as all samples were compared against this value.

3.8.2 COD General Considerations

The test measuring Chemical Oxygen Demand (COD) was employed to determine the oxygen equivalent of the organic material of a sample that is susceptible to oxidation by a strong chemical oxidant (APHA, 1998). This test was founded on the grounds that nearly all organic compounds can be oxidized by the action of strong oxidizing agents under acidic conditions (Sawyer et al.,1994). The Chemical Oxygen Demand often exists in a stable relationship with the Biochemical Oxygen Demand (BOD). Once a correlation has been established between the COD and BOD, the COD value can be used to calculate estimates of the BOD.

Unfortunately the COD test is unable to differentiate among biologically degradable and biologically inert compounds. The COD test converts organic matter to carbon dioxide and water regardless of the biological assimilability of the substances. This results in COD values, which are greater than BOD values (Sawyer et al. 1994). Also the test gives no information on the rate of degradation in the natural waters. This test was relatively simply to perform and like suspended solids was used extensively to determine the operational procedures used for the test unit as well as for experimental design and parameters of the final testing scheme.

3.8.2.1 COD Procedure

First, 3.5 mL of digestion reagent (10.216 g $K_2Cr_2O_7$, 167 mL conc. H_2SO_4, 33 g $HgSO_4$ all diluted to 1000 mL with reagent grade water) was added to a 10 mL sealable test tube with 2 mL of Micro-COD reagent (9.715 g Ag_2SO_4 / L H_2SO_4) and 2 mL of sample. The test tube was sealed and digestion was started in the Hach digestion unit. Digestion lasts for two hours at 140°C on the Hach micro-COD digestion block. The samples were cooled and placed in the Bausch and Lomb Spectronic 21 spectrophotometer to measure absorbance (A_{600nm}), which was zeroed using blank samples, to obtain absorbance readings. The results were then calculated using a linear best fit equation from the absorbance vs. known COD concentration graph made from the known standards. A new calibration curve was made every time a new reagent solution was required.

The standards for this project included the following:

-Blank DI Water

-Std 1: 50 ppm Carbon (from potassium hydrogen phthalate)

-Std 2: 100 ppm Carbon (from potassium hydrogen phthalate)

-Std 3: 200 ppm Carbon from potassium hydrogen phthalate)

-Std 4: 300 ppm Carbon (from potassium hydrogen phthalate)

-Std 5: 400 ppm Carbon (from potassium hydrogen phthalate)

-Std 6: 800 ppm Carbon (from potassium hydrogen phthalate)

-Std 7: 1000 ppm Carbon (from potassium hydrogen phthalate)

Additionally blanks and standards were run along with every digestion to ensure the continued accuracy of the standard curve and to calibrate the spectrophotometer. Samples were stored by adding concentrated sulfuric acid to bring to a pH of >2 and stored usually for less than a week and never more than 30 days.

3.8.2.2 COD Data Quality Assessment

The data quality of the COD experiments was excellent. Triplicate analysis was performed early in the testing (for all samples to March 21, 2001) while duplicate analysis was used for all samples past that time as the triplicate results were consistently all the same absorbance or just off by 0.001 (A_{600nm}). The standard deviation of differences for duplicate measures from test runs for July 9,11,13,17 and

19 was 8.2 mg/L with an average COD of 212 mg/L. This was reasonable when compared to precision values given by Standard Methods (APHA, 1998).

3.8.3 Total Phosphorus, General Considerations

Quantification of total phosphorus required the digestion of all phosphorus forms to dissolved orthophosphate followed by a colorimetric determination of dissolved orthophosphate. Selection of method for use with this project involved considerations of test time, detection limits, material costs, available resources and safety. Standard Methods (APHA, 1998) was used as the basis for the examination.

The digestion (oxidation) of organic phosphorus can be accomplished using perchloric acid, nitric acid-sulfuric acid, or persulfate (APHA, 1998) with the persulfate technique being the least time consuming and safest. While three colormetric methods (the Vanadomolybdophosphoric acid colorimetric method, the Stannous Chloride method and the ascorbic acid method) exist for the final concentration determination. The persulfate digestion with the ascorbic acid colormetric method was used because its detection limits (0.2 mg/L to 20 mg/L) would encompass the range of the expected concentrations from the primary effluent and the Electrofloc^{PLUS} treated effluent. The ascorbic acid colorimetric method was performed both manually and in-line using the Perstolp analytical EnviroFlow 3500 with earlier sample being done manually while the later samples were measured in-line. This was because early on the autoanalyzer was not working. These methods were conducted as prescribed by Standard Methods (APHA, 1998) and the Perstolp analytical EnviroFlow 3500 user manual (1994). The samples were preserved by adding concentrated sulfuric acid to a pH < 2 (approx 1 mL per 250 mL sample) and then stored at 4°C. All samples tested were well within the Standard Methods (APHA, 1998) recommended holding time of 28 days (usually tested within 2 weeks).

3.8.3.1 Persulfate Digestion (for manual colorimetric analysis)

First 50 mL sample was pipetted into 125 mL digestion vessels and add 1 drop phenolphtholein and if the sample turned red add 11 N H_2SO_4 solution until colorless and then 1 mL more 11 N H_2SO_4 was added. Then 0.4 g solid Ammonium persulfate was added. The sample was autoclaved for 30 minutes at 121 °C, 137 kPa and then cooled. One drop of phenolphtholein indictor was added and then NaOH solution was added to a faint pink then dilute sample to a volume of 100 mL in reagent grade water.

3.8.3.2 Persulfate Digestion (for automated colorimetric analysis)

The procedure is the same as Persulfate Digestion (for manual colorimetric analysis) except that the phenolphthalein indicator was not used. This was the procedure given in the EnviroFlow 3500 manual (1994).

3.8.3.3 Ascorbic Colorimetric method (manual)

First a volume of digested sample was taken from the digestion vessel and put into a 125 mL Erlenmeyer flask (the volume used depends on the expected phosphorus concentration usually 10 or 25 mL sample was used). The sample was then brought to 50 mL with reagent grade water. One drop of phenolphtholein indicator was added and if red then 5 N H_2SO_4 was added until the solution was colorless. Then 8 mL of combined color reagent was added and the color was allowed to develop for ten minutes. The absorbance at 880 nm of the sample was then measured using Pharmacia Biotech Ultrospec 3000 with 10 mm cuvet

3.8.3.4 Ascorbic Colorimetric method (automated)

The theory and steps involved in automated method are similar to those for the manual method only that they are conducted in-line. The automated method was performed according to the operating procedures supplied in the EnviroFlow 3500 manual (1994). The standard curve and calculations were made using the ALPKEM Enviroflow software version 2.00 (revision 49) as the data from the autoanalyzer was uploaded into this program. For all samples, blanks and standards the peak absorbance for each sample used in the calculation to determine total phosphorus concentrations were first established automatically by the software and then verified for correctness by a manual review.

3.8.3.5. TP Analytical Quality Assessment

The total phosphorus analytical results were quite good when using both the manual and inline procedures. For example using the manual method the average difference between duplicates for tests run on 26 samples from March 12, and March 14 testing was 0.02 mg/L (average measured concentration 2.48 mg/L). For the inline method the average difference between 34 duplicates was 0.03 mg/L (average measured concentration 1.37 mg/L). Standards measured within a test run to confirm the continued accuracy of the calibration curve always confirmed the continued accuracy of the calibration. There was no evidence to suggest interfering compounds were causing accuracy problems with the tests.

3.8.4 Nitrogen Forms General Considerations

Nitrogen exists in various forms in the environment including organic nitrogen, ammonia nitrogen, nitrite and nitrate nitrogen. Nitrogen forms when under aerobic conditions naturally progresses from one form to another in order as stated. All forms were of some interest for the project so all were measured with varying success.

3.8.4.1 Ammonia and TKN General Considerations

For the measurement of ammonia Standard Methods (APHA, 1998) contains four methods which are available including two colorimetric procedures (by direct nesslerization or direct phenate addition these can also be preformed after a distillation step) , a volumetric procedure (using a distillation and titration process), and an instrumental procedure utilizing a ammonia-selective membrane probe. The method selected for use was the volumetric procedure as this method provided the accuracy necessary within the concentration range of interest and laboratory equipment for this test was available.

For the measurement of Total Kjeldahl Nitrogen the sample was first digested in order to convert all nitrogen present as organic compounds into ammonia. After this process was complete the remaining ammonia could be measured using one of the aforementioned techniques. The total amount of organic nitrogen present was then be calculated by taking the difference between the Total Kjeldahl Nitrogen and the ammonia nitrogen.

3.8.4.2 Procedures (Ammonia and TKN)

For the TKN analysis first a digestion step was used to convert all nitrogen forms into ammonia so that volumetric procedure can be performed. This was done using the Tecator Kjeldahl 2020 digestion apparatus and 250 mL digestion tubes. First an Anachemia No. CT-37 (3.5 g K_2SO_4 + 0.4 $CuSO_4$) Kjeltab and one boiling rod was put in each digestion tube along with a 50 mL aliquot of sample. Then 12 mL of conc. sulfuric acid was added under the fume hood and the samples were put into a stainless steel rack that was transferred into the Tecator Kjeldahl 2020 digestion apparatus. The digestion was conducted under the fume hood and operation of the digestion apparatus was conducted according to the operating manual (Tecator,1995). Once the samples had been digested they were allowed to cool for at least 30 min and no more than 2 hours.

The distillation was performed using the Tecator 1026 distillation apparatus operating the apparatus according to the operating instruction manual (Perstolp,1995). The digested sample was left in the digestion tube and placed in the Tecator 1026 apparatus. The tecator apparatus serves to perform the distillation which separates the ammonia from interfering substances (Sawyer et al., 1994). The tecator 1026 adds 75 mL of deionized water and 100 mL of sodium hydroxide and then injects steam directly into the sample for 3.6 minutes. The condensate from the tecator 1026 apparatus was collected in a 25 mL aliquot of 4% boric acid receiver solution with methyl red indicator.

The methyl red indicator was not required as the process selected used the Mettler Telodo DL50 autotitrator. Which was operated according to the user manual instructions (Mettler Telodo,1995) and was calibrated before use with commercial pH buffers. The methyl red served as a visual aid to ensure that the autotitration process was operating correctly (i.e. the titration stopped after the color changed indicating that the endpoint had been reached). The endpoint used was determined by taking the 25 mL boric acid solution and adding the equivalent amount of reagent grade water that was added as condensate when run through the Tecator 1026 distillation apparatus (approx. 200 mL) and tested for its pH on the autotitrator. This process was repeated three times and the average found was used as the endpoint. The samples, blanks and standards were then titrated with 0.005 N hydrochloric acid using the autotitrator to the established endpoint and the volume used was recorded. Sawyer et al. (1994) recommended this potentiometric method as it eliminates the need for internal indicators. The TKN can be calculated according to the following formula

$$\text{mg/L TKN} = (T-B) * 14.007 * N * 1000 / \text{mL of sample} \qquad (3\text{-}4)$$

Where: T = mL of titrant used for sample

B = mL of titrant used for blank

N = Normality of titrant (0.005 N HCl)

14.007 = Automic weight of nitrogen

1000 = Conversion from mL to L

For the ammonia analysis the same procedure as above is followed only skipping the initial digestion. All sample were preserved by bringing the pH to <2 with concentrated sulfuric acid. Most Electrofloc^{PLUS} treated samples were tested for TKN and ammonia within 3 weeks of the test run. For each batch of digested samples (all those being digested at the same time) two blanks and two 25 mg/L standards were run. All samples were analyzed in duplicate. For ammonia because there was no digestion step and no limitation to how many could be analyzed during a single testing session triplicates rather than duplicates were used for the blanks and standards.

3.8.4.3 Ammonia and Total Kjeldahl Nitrogen Data Quality Assessment

For the ammonia samples the average difference between duplicates for tests run on July 13, 17 (16 wastewater samples) was 0.07 mg/L (average measured concentration 18.6 mg/L). While for TKN the average difference between duplicates for the same samples was 0.66 mg/L (average measured concentration 20.9 mg/L). The increase in the difference between duplicates for the ammonia and TKN sample is attributable to the extra digestion step involved in the TKN analysis.

The standards appear to have some level of bias associated with them. Table 3-2 shows the average recovery of the standards run along with the samples treated with the aluminum electrode. For Table 3-2 the analytical precision 95% confidence interval is ± 1.1 mg/L for TKN while for ammonia the 95% confidence interval is ± 0.1 mg/L.

Table 3-2 Ammonia and TKN Standard Results

		Ammonia	TKN
Samples	Std conc.	Conc.(mg/L)	Conc.(mg/L)
0510R1&2	25 mg/L	26.9	25.8
0523R1&2	25 mg/L	26.2	27.5
0709R1&2	25 mg/L	26.0	28.0
0711R1&2	25 mg/L	26.8	Lost
0713R1&2	25 mg/L	26.5	23.5
0717R1&2	25 mg/L	26.6	26.5
0719R1&2	25 mg/L	26.5	27.0
	Average	26.5	26.4

As can be seen from these results the standards are typical 6% higher than expected. It is also important to note that due to a breakdown to the distillation system the test runs from 0713R1 & 2, 0717R1 & 2 and 0719R1 & 2 were stored for approximately 2 weeks beyond the maximum recommended storage (28 days) according to Standard Methods (APHA, 1998).

3.8.4.4 Nitrites and Nitrates General Considerations

For nitrates (NO_3^-) four generally used procedures exist including screening by ultraviolet spectrophotometry, an ion chromatographic method, a nitrate electrode method and a cadmium reduction method. Nitrite is generally rapidly converted to nitrate so the two are generally measured together as was the case with this project (Thomann and Mueller, 1987). In fact when storing samples after acidification the two forms must be measured together (APHA, 1998). This was done using the cadmium reduction which converts all NO_3^- to NO_2^- and then the diazotization colorimetric method. For this combined procedure an automated procedure is given in "Standard Methods 4500- NO_3^- F. Automated Cadmium Reduction Method" and was used for this project. Standard Methods (1998) suggest that the nitrate and nitrate determination is difficult to perform because of the complex procedures involved and a high probability of that interfering constituents will be present.

3.8.4.5 Procedures (Nitrite and Nitrate)

Samples were preserved by applying concentrated sulfuric acid to a pH of <2 and stored and 4°C. Samples were generally tested within a week of the test run and none were tested beyond two weeks. A standard curve was made by using 1000 mg/L nitrite stock and diluting to 0.05 mg/L ,0.5 mg/L,1.0 mg/L, 2 mg/L, 3 mg/L and

4 mg/L also a reduction test was preformed on a 4 mg/L solution of nitrate. The standard curve was then used to determine the concentration of the remaining samples. The standard curve and calculations for determining concentration were made using the ALPKEM Enviroflow software version 2.00 (revision 49) as the data from the autoanalyzer was uploaded into this program.

3.8.4.6 Nitrate and Nitrite Nitrogen Data Quality Assessment

The data quality of these tests was difficult to assess for two reasons. First it was very difficult to get the autoanalyzer to effectively operate with the standards in order to make a standard calibaration curve. Second low levels of nitrites + nitrates in the wastewater itself made it difficult to troubleshoot performance.

Since the quality of the data were in question the results should be understood as being qualified. It is recommended that for future research a small group of samples be outsourced to another lab so that a comparison can be made and the correctness of the results assessed. The nitrate + nitrite test was difficult and complex as stated by Standard Methods (APHA, 1992) and discussed in section 3.8.4.4 which makes troubleshooting and quality assessment difficult.

Only six test runs of data were successfully completed (0711R1 & R2, 0713R1 & R2, 0717R1 + R2, 0719R1). The samples for 0719R1 & 2 were performed during a successful run but a bubble in the middle of the sample set invalidated the data for the PE and the initial sample so this set was not used as the initial value was unknown. Standards were randomly tested in-between test samples to ensure the continued accuracy of the standard curve. A 1 mg/L standard showed a result of 1.00 mg/L, a 0.5 mg/L standard showed a result of 0.52 mg/L when tested between samples, the third standard of 1 mg/L yielded a result of 1.08 mg/L. A 2 mg/L standard showed a result of 2.18 mg/L when test in between samples. These standard results do not instill great confidence in the final data.

The average difference between duplicates was 0.03 mg/L which was quite high considering the low concentrations tested.

3.8.5 BOD_5 General Introduction

The amount of biologically oxidizable organic matter present is determined by the use of the five day Biochemical Oxygen Demand (BOD_5) test. For waters that have high BOD release into the environment would result in anoxic conditions as the transfer rate of oxygen from the air to water is slower the dissolve oxygen being depleted by the BOD. This type of DO stress has environmental problems as outlined in Table 2-3. The basic concept of the BOD_5 test is to measure a samples dissolved oxygen after collection and then measuring the dissolved oxygen after 5 days while ensuring that biological population is present to utilize the organic matter. The decrease in oxygen over the five days is the BOD_5. Dilutions and stringent controls are of course necessary as this bioassay, like all bioassays, is very sensitive to environmental test conditions used.

3.8.5.1 BOD_5 Procedure

The tests were conducted according to Standard Method procedures (APHA, 1998) in room lab 218, in the Environmental Engineering Building. First dilution buffer containing 1 mL of phosphate buffer, $MgSO_4$ solution, $CaCl_2$ solution and $FeCl_3$ solution (each solution was pre-prepared according to Standard Methods) was made the previous afternoon that the testing was to occur. Oxygen was slowly supplied to the dilution buffer through the use of an aquarium bubbler overnight. The next day fresh primary effluent sample was collected and the test unit run. The raw sample and treated sample from the test unit was then tested for BOD_5 as shortly after the test run as possible (usually within 1 hour).

First a dilution blank was collected in triplicate to ensure that the DO uptake of the dilution buffer was less than 0.2 mg/L. Then a small amount of seed (untreated primary effluent) was added to the dilu[illegible] buffer to ensure a significant biological population is present to oxidize the organic matter in all samples. This was generally 3.33 mL per litre of dilution buffer so that the final amount of seed used per DO bottle was 1 mL. In order to correct for the uptake from the seed a seed blank was taken in triplicate.

Dilutions were then made directly in the BOD bottle as directed by Standard Methods (APHA,1998). Nitrification was not generally inhibited however, in one test run a set of nitrification inhibited samples and blanks were run to provide a comparison with the theoretical estimation. This was done by adding 3 mg 2-chloro-6-(trichloro-methyl) pryidine (TCMP) to each BOD bottle being tested for CBOD.

The various sample dilutions were prepared using the method outline in Standard Methods (APHA, 1998) for preparing dilutions directly in the BOD bottle when analyzing using the membrane electrode method for dissolved oxygen determination. (When using Winkler titration to cross check the dilutions for these were prepared according to the standard procedures for this method.) The goal was to have a DO uptake of at least 2 mg/L and a residual DO of at least 1 mg/L as this is stipulated as the acceptable range according to Standard Methods. The goal was to select a dilution that would get about a 5 to 6 mg/L uptake. The initial DO was measured in each dilution bottle using the DO electrode (except when checking against the Winkler titration), which was calibrated using air pressure and temperature readings. The DO electrode was usually turned on early in the day to allow it to "warm up" and recalibrated through the day. The bottles were then stoppered (with enough water present to allow a water seal), capped, and put in the 20 °C temperature controlled room in the dark for a 5 day incubation and the DO measurement was repeated on day 5 of the test. (When the Winkler methods was used enough sample dilutions were made to test on triplicate set on day 0 and the other triplicate set on day five. The samples bottles selected for testing on day 0 and on day five were chosen randomly.) Triplicate analysis of a glucose-glutamic acid check was also performed as part of this test to allow for comparison with established values.

3.8.5.2 Winkler Titration verses DO Electrode methods for Dissolved Oxygen Measurement

Two methods are typically used for the dissolved oxygen measurements in the BOD tests. Standard Methods (APHA, 1998) details both methods as acceptable as part of the BOD experiment and also explains preparation deference's and procedure differences for each method. Both tests were conducted at different times according to Standard Methods (APHA 1998). The membrane electrode was used primarily while the Winkler titration was used once to double check the DO electrode results.

3.8.5.3. BOD Data Quality Assessment

The BOD data quality was not nearly as good as the COD data. The following table lists the results of the glucose-glutamic acid check which is to be used as a reference from which the evaluation of dilution, water quality, seed effectiveness, and analytical techniques(APHA, 1998) and suggests 198 mg/L ± 30.5 be used as a general control (The 30.5 value is the standard deviation value from multi-lab tests) . Table 3-3 summarizes the results of the glucose-glutamic from the testing days analyzed for BOD.

Table 3-3 BOD Glucose-Glutamic Acid Check and Performance Checks

Test Samples Analyzed	Glucose-Glutamic BOD.	Meets Criteria (167.5 to 228.5)	Seed Uptake (mg/L)	1 mg/L DO residual	Didn't meet 2 mg/L uptake requirement
0510R1 & R2	96	No	n/a	All	None
0523R1 & R2	169	Yes	0.30	All	R1-1
0709 R1 & R2	171	Yes	0.80	All	R2-1, R1-1
0711R1 & R2	159	No	0.47	All	All
0713R1 & R2	142	No	0.32	All	R1-1, R1-3, R2-1, R2-3, R2-5, R2-7, R2-7B
0717R1 & R2	161	No	0.42	All	None
0719R1 & R2 (Winkler)	177	Yes	0.54	All	None
0719R1 & R2	166	No	0.64	All	None

From this it can be seen that the overall results were less than impressive. However, all samples had at a D.O residual of least 1 mg/L and most samples met the 2 mg/L uptake requirement. The apparent problem with the glucose-glutamic check results seems to be the seed uptake was not within the Standard Methods recommended uptake of 0.6 to 1.0 mg/L (APHA, 1998) as it can be seen that for the May 10 results (no seed used this day) very little uptake was found in the glucose-glutamic check but for the others more uptake was discovered and the glucose-glutamic values appear to be related to the seed uptake. It is believed that if more seed were used the glucose-glutamic check would have been in the appropriate range. However, for these samples the seed was not necessarily required at all because the raw primary effluent sample used is in fact the recommended seed source for BOD_5 tests. The electrofloc treated sample may not be recommended but it should have still had sufficient characteristics to work as a seed. Therefore, it was concluded that the poor glucose-glutamic results do not invalidate the findings but for all samples measured from those days the results are qualified. Also for the samples which did not meet the 2 mg/L uptake the results are also qualified which includes all of the samples from July 11 and many of the samples from July 13 for most of these the uptake was near 2 mg/L. These samples were not going to be considered in the final analysis. Concerns over the calibration of the membrane electrode DO meters lead to a parallel test using the Winkler titration and the membrane electrode for the measurement of BOD_5 to compare the results and check for agreement. The comparison was performed with treated sample from July 19 and the test unit operating conditions included ozone addition with the aluminum electrode. The results of the comparison are found in Table 3-4.

Table 3-4 Comparison Between Winkler and DO Electrode Method

Sample	Winkler BOD_5 (mg/L)	DO Electrode BOD_5 (mg/L)	Difference (mg/L)
Glucose-Glutamic test results	177	166	11
0719R1 & 2 Raw PE	175	171	4
0719R1 1 pass (56 A applied)	115	105	10
0719R1 7 passes (403 A applied)	88	88	0
0719R2 1 pass (59 A applied)	120	119	1
0719R2 7 passes (421 A applied)	88	83	5

As the DO electrode results are not that far off the Winkler test results, yielding slightly higher values, the DO electrode values will be used for discussion. Nitrification was only used in one case to determine if many nitrifying organisms were present. Standard methods suggests that primary effluent contains very few to no nitrifying organisms and that inhibition is not required (APHA, 1998). The electrofloc process is not a biological process so the number of nitrifying organisms will not increase after the treatment process and therefore nitrification can be considered negligible. Also Liu and Liptik (2000) suggest that NBOD does not start at all until after day 5 with raw domestic wastewater so as not to impact a BOD_5 day test. To confirm this a $CBOD_5$ test was performed (with nitrification inhibitor). The results of the $CBOD_5$ test and the results of the comparative BOD_5 test are found in Table 3-5. Test was performed with sample from July 17 and the test conditions included ozone addition with the aluminum electrode.

Table 3-5 Comparison Between $CBOD_5$ and BOD_5

	$CBOD_5$ (mg/L)	BOD_5 (mg/L)
0717R1& R2 - Raw PE	141	150
0717R1, 7 passes (403 A applied)	51	59
0717R2, 7 passes (421 A applied)	60	55

From this it can be seen that there was little difference between the two so that for these sample BOD can be considered approximately the same as CBOD perhaps being slightly higher.

3.8.6 Microbiological Assessment General Considerations

To assess the reduction and kill of pathogens in the Electrofloc^{PLUS} treated samples three techniques/indicators were used. These included fecal coliform determination, *Bacillus subtilis* and a *Cryptosporidium spp.* infectivity test with CD-1 mice. The fecal coliform testing was performed according to Standard Methods (APHA, 1998) and was completed with the assistance of Ms. M Detmer, Laboratory Assistant with the Environmental Engineering Program. The *Bacillus subtilis* counts and the *Cryptosporidium spp.* infectivity tests were performed using methods developed by previous researchers at the University of Alberta. The *Bacillus subtilis* testing was performed for Craik's (2001) research while the *Cryptosporidium spp.* methods used in this project were developed by previous researchers at the University and have been used for a variety of studies including (Craik, 2001). Mr. E. Guigard, Laboratory Assistant with the Environmental Engineering Program, assisted with the *Bacillus subtilis* testing. The *Cryptosporidium spp.* analytical work was preformed by Mr. Guigard and Mr. C. Kucharski, Laboratory Assistant with the Department of Biosciences. Both Laboratory Assistants were experienced in the methods derived from the aforementioned study. Additional discussion of both the *Bacillus subtilis* and *Cryptosporidium spp.* analytical techniques and there limitations are available in (Craik, 2001).

3.8.6.1 Fecal Coliform Membrane Filtration Procedure

The procedure followed for this project was derived from the Standard Methods procedure 9222 D. (APHA 1998). This test was performed at the University of Alberta, Newton Research Laboratory in room #437. Figure 3-7 summarizes the processes involved in the procedure.

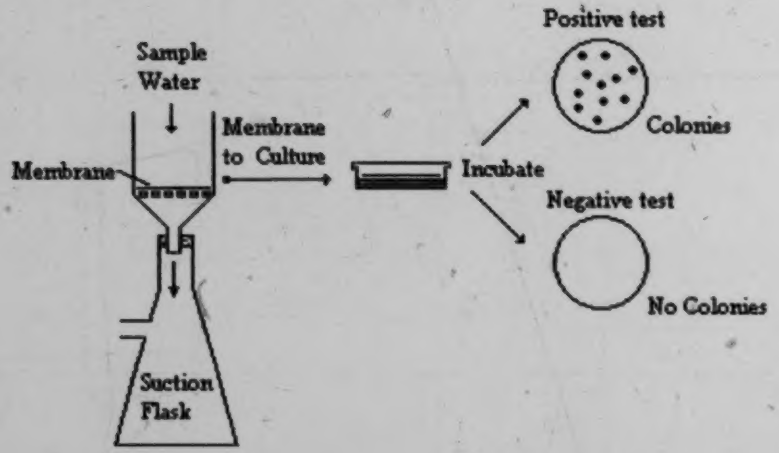

Figure 3-7 Basic Steps of Membrane Filtration Technique

Ideally for fecal coliforms the plate counts should fall between 20 to 60 colonies (APHA, 1998). When the value falls within this range it can be considered representative. This value is somewhat restrictive because of the large size of fecal coliform colonies. Thus, sampling for coliforms required samples be processed at different dilutions to ensure that a representative sample was obtained. For this project 3 dilutions were used for each sample within the expected range in an attempt to get a count within the 20 to 60 desired (when no counts were within this range the closest to the count was used). Appendix B contains the microbiological data and the colony counts To add statistical strength to the results each dilution was analyzed in triplicate. Therefore all the countable plates are considered in determining coliform density as follows.

$$\text{CFU/100mL} = \frac{\text{coliform colonies counted} \times 100}{\text{mL sample filtered}} \qquad (3\text{-}5)$$

As a check on the method a test was performed to determine that the procedure was not resulting in high counts (i.e. contamination somewhere within the procedure). The check involved boiling a raw primary effluent sample for five minutes on a hot plate then running through the same sample collection and analysis procedures as the other electrofloc treated samples. This resulted in triplicate plate counts of 0 CFU/100 mL at all dilutions including filtering sample volumes of 25 mL, 10 mL and 1 mL. A check of plate counting procedures was also conducted during the analysis of each set of samples. At least two plates were counted twice to verify the accuracy of the counts. These counting checks always resulted in less than 5% discrepancy between counts which is within the range suggested by Standard Methods. One other counting check was performed to ensure that the counting procedure used was consistent with other lab analysts. Another lab analyst also doing microbiological plate counts counted two plates from samples for this project and were compared to the counts that had already been preformed and the results agreed to within 5% which is better than the 10% limit given by Standard Methods for counts between different analysts.

Each sample dilution was tested in triplicate and each dilution was analyzed to ensure that it fit the Poisson distribution. This is important as it shows that the organisms are randomly dispersed in the sample and allows the appropriate use of confidence limits that follow Poisson statistics (Haas and Heller, 1985). The following calculation is used compared to the χ^2 statistic at the desired level of significance (α).

$$D^2 = \frac{(n-1)s^2}{\bar{x}} \quad (3\text{-}6)$$

Where: D^2 is index of dispersion,

s^2 is the estimate of the population variance,

$\bar{x}$ is estimate of population mean, and

n is sample size.

The 95% confidence limits are then calculated using the following equation.

$$C \pm 2\sqrt{C} \quad (3\text{-}7)$$

Where C is number of colonies counted.

3.8.6.2 Fecal Coliforms Data Quality Assessment

Most samples with the acceptable colony counts passed the D^2, index of dispersion test (compared to χ^2 critical value of 5.99 (0.05 significance level, 2 d.f.)) which suggests that the sample was well mixed and randomly distributed according to Poisson statistics (Haas and Heller, 1985) and the confidence interval formula given in Standard Methods can be used. There were a few non-fecal colonies observed but these were only a few and were easily identifiable. A check on the method was performed by boiling a primary effluent sample and then conducting it to the same testing protocols as the other primary effluent samples (with the exception being that it was subject to different dilutions). In this test on the method no coliforms were counted on the plates with the boiled primary effluent. Appendix B show the results of the plate counts, if they meet the 20 to 60 plate count limit and if they meet the assumption of Poisson distribution.

3.8.6.3 *Bacillus subtilis* General Considerations

The use of aerobic *Bacillus subtilis* spores as a measure of reduction efficiency/kill in wastewater treatment is a relatively new technique. This method is very similar to the fecal coliform method with the primary difference being the growth media and temperature used. The *Bacillus subtilis* analysis utilizes trypticase soy broth and a temperature of 35 °C for 22 to 24 hours. The *Bacillus subtilis* analysis however also involves an additional step. After filtration and prior to incubation the plates are placed in a dry air oven at approximately 72 to 75 °C for 20 minutes in order to inactivate any vegetative cells to reduce the likelihood of non-bacillus colonies being formed. For each experimental sample the preparation of the dilution series and the plating was performed in triplicate.

For the majority of the testing the Goldbar WWTP primary effluent samples were spiked with a known amount (1.2×10^9 CFU / 30 L) *Bacillus subtilis* spores strain number 6633 prior to being sampled and treated. This was done so that the spiked spores would allow dilutions at sufficient levels to prevent interference from the wild strains. The wild strains were measured at 1.17×10^4 CFU/ 100 mL in raw primary effluent therefore a 1.2×10^9 CFU / 30 L addition was required to give finals concentrations at around 4.0×10^6/100 ml thus far exceeding the wild strains and eliminating the likelihood of interference from the wild strains. The laboratory cultivated spores were grown following methods reported in (Craik, 2001). Calculations for *Bacillus subtilis* are the same as for fecal coliforms.

3.8.6.4 *Bacillus subtilis* Data Quality Assessment

The *Bacillus subtilis* data quality is good. Most samples pass the D^2 is index of dispersion test (compared to χ^2 critical value). The colonies were very distinct with little interference especially when the samples were spiked. For the unspiked samples there appeared to be some interference with non *Bacillus subtilis* colonies but it was not at a serious level. With every sample set blanks were run to ensure that there was not contamination from glassware etc. All blanks tested contained no colonies. Appendix B shows the results, confidence limits and D^2 test results for all test results reported.

3.8.6.5 *Cryptosporidium spp.* General Considerations

Cryptosporidium spp. challenge tests were done as spiked samples as 13.2 million oocysts / L were added to the collected wastewater (and therefore a large *Cryptosporidium spp.* source was required to be produced). *Cryptosporidium spp.* production and purification methods for running *Cryptosporidium spp.* challenge tests were developed and used for previous studies at the University of Alberta (Craik 2001). These previously developed methods were used for this study. Spiking the wastewater was required to ensure that there was sufficient *Cryptosporidium spp.* present to determine their reduction.

The calculations were performed according to the Logistic Dose Response model cited in Craik (2001) using a standard Microsoft Excel template for the calculations. The methodology for *Cryptosporidium spp.* allows for the identification of the actual kill within a treated sample and that is what was determined from the analysis as opposed to the reduction (i.e. all *Cryptosporidium* *spp.* remaining after treatment were counted and an infectivity analysis of the remaining oocysts was preformed using neonatal mice).

3.8.6.6. *Cryptosporidium spp.* Data Quality Assessment

These procedures were conducted without the help of the primary researcher so a detailed description of the data quality is not possible. The lab technicians responsible stated that the testing went well and that good counts were possible. The main problem was that not enough *Cryptosporidium spp.* was recovered to test the most concentrated sample desired but in the end it was not needed as the lower dilutions proved to fit the right inactivation level.

3.8.7 Metals General Considerations

The impact of metals on the receiving environment is greatly dependant on the concentration with some metals being beneficial and required by the receiving environment at certain concentrations while at other concentrations they can be extremely toxic. The Electrofloc^{PLUS} system utilizes similar technologies to some that are used for metals extraction and therefore metals were of interest to see what was happening with them in the wastewater. As well research has shown that electroflocculation will remove metals for certain industrial and mining waste streams (Rock, 1996). The use of aluminum electrodes causes the addition of this element to the wastewater therefore it was desirable to determine were and what was happening to it. Therefore, three streams of the wastewater were tested on three separate occasions. These included the raw primary effluent, the electrofloc treated and separated effluent, the electrofloc treated and blended effluent and the sludge waste from the top of the samples.

3.8.7.1 Testing Protocols

The metal analysis was outsourced to the Goldbar Wastewater Treatment Plant laboratories for analysis (the results released by Goldbar can be found in Appendix E). The method used was taken directly from Standard Methods (APHA, 1998) and is known as the Inductively Coupled Plasma (ICP) method with a Nitric acid digestion. The samples were stored in trace metal grade containers and acidified using nitric acid to bring the sample to a $pH < 2$. Metals tested for using this method included Ag, Al, As, B, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Se, Tl and Zn. The samples were all tested within three weeks of being treated. The precision and bias is different for each element and can be found in Standard Methods (APHA, 1998).

3.8.7.2 Sludge Extraction

For the metals analysis this required that a technique be developed for the isolation of the sludge from the sample in order to get reliable results for the sludge stream. To do this the Electrofloc^{PLUS} treated sample was collected into the holding tank and allowed approximately three minutes for the initial stages of the flotation process to occur. The water on the surface was then skimmed off using a bucket and poured into three Imhoff cones. Because of the skimming process the remaining wastewater was no longer suitable for further passes through the system, as the sample would not be representative. Therefore during these test runs the sample for metal analysis had to be collected at the end of the run and no intermediate samples were possible.

The Imhoff cone had been previously designed with a hose and clamp attached to the bottom. After the normal flotation period the clean water under the sludge was drained until a significant amount of sludge had flushed through the hose. The remaining sludge in the Imhoff cone was then collected in trace metal grade sample containers, acidified for storage and then sent to Goldbar WWTP laboratories for analysis. The problem identified with this method was the sludge may not have been as thick as after collection than when it is on top of the sample. This is because a small amount of solid sludge particles became visibly attached to the short hose at the bottom of the Imhoff cone. However, in comparison to the volume of sludge collected this was a very small amount and did not likely impact the results greatly. One of the modified Imhoff cones can seen Figure 3-8.

Figure 3-8 Modified Imhoff Cone for Sludge Extraction

3.8.8 Conductivity, pH and Temperature

These parameters were measured using a Fischer Scientific Accumet 50 Conductivity/ pH/Ion meter. The temperature was measured with the attached temperature probe. The pH was calibrated regularly using commercial buffers. The conductivity was calibrated regularly using a prepared 0.01 M KCl solution which was brought to 25°C by a Fischer Scientific Isotemp waterbath as instructed by

Standard Methods (APHA, 1998). At this temperature the conductivity of the water is exactly 1412 μS/cm. The conductivity probe was a standard Accument glass body conductivity electrode.

3.8.9 Miscellaneous Methods

3.8.9.1 Reagent Grade Water

For experiments preformed reagent grade water was taken from Elga Maxima Ultrapure Water which produces HPLC grade water.

3.8.9.2 Weighing

For weighing dry chemicals to make reagents and standards the Mettler AE166 analytical balance was used. For weighing salt to increase the conductivity of wastewater the Mettler PE 3600 was used.

4.0 Results / Discussion

For this project a large amount of experimental data was produced. In total 21 wastewater samples were treated with the system in single pass setup with 39 different test runs (a test run being defined as a fresh volume of wastewater sample being run through the test unit under a specific set of conditions for a designated number of passes through the test unit) with 396 passes through the unit. An additional 15 wastewater samples where collected and treated in batch mode. In total approximately 280 different samples from the various treatment passes and raw PE were tested for suspended solids while 260 have been tested for COD, 180 for total phosphorus, 85 for ammonia, 76 for TKN and 86 for BOD_5. Additionally, 12 samples were tested for metals, 22 successfully tested for nitrates + nitrites, 36 samples were tested were tested for fecal coliforms, 12 for *Bacillus*, 3 for

Cryptosporidium spp. infectivity. In addition numerous temperature, pH, and conductivity measurements were made.

This section will outline the results of the experimentation and discuss their implications. First the experiments that define the basic operations of the unit will be examined particularly water flow rate, ozone dose, salt addition and flotation time. Then this section will illustrate and briefly summarize the results of the preliminary and phase one tests. The phase two testing results will then be discussed. Test unit variability for these experiments will be considered first. Then identifying the test unit performance under different testing conditions will be examined. The results from each water quality param[illegible]ested will then be discussed in terms of the impacts of the electroflocculation process on that particular parameter. Power consumption will be addressed and a general overall view of the results will be discussed in reference to test unit performance and the experimental design used. To finish the section, a discussion on a summary of the results and there implications, possible applications of the technology, limitations of this study, future directions for the technology and recommendations for further electroflocculation research. Additionally, a summary of optimal system performance in comparison to the effluent standards and regulations discussed in section 2.2 will be completed.

4.1 Test Unit Operations

This section will define the basic operations of the test unit and related source water issues as they impact the test unit's operation. As such the flow rate determination, ozone dose determination, conductivity change of source water and flotation time used are discussed.

4.1.1 Flow Rate

The flow rate of the test unit was determined by simply timing how long a certain volume took to pass through the system as discussed in section 3.6. The problems with this method included not being able to determine the volume accurately due to the foam and froth on the water surface making the exact volume difficult to see. This problem was primarily seen only during the last few passes of a test run. Also, the water was often unstable (i.e. turbulent waves) which also made the exact volume difficult to read. This test was run intermittently on sample treatment days and also during the ozone dose tests. Another factor contributing to variable results included the difficulty to perform the test while monitoring the rest of the system; often the help of an assistant was required. Since this was commonly not the same person the standard for measuring the volume decrease and the quickness of the hand on the stopwatch was different on different days. However, the results were still quite consistent with highest flow rate ever being timed was 0.76 L/s while the lowest flow rate recorded was 0.62 L/s while the majority of samples were between 0.64 L/s and 0.71 L/s. The average and standard deviation for all individual tests worked out to be 0.68 L/s and 0.04 L/s, respectively. This average and standard deviation tests conforms very closely with tests preformed on Feb. 22, 2001 specifically to determine the flow rate and used and monitored a much higher volume (34 L) than was possible during a normal treatment run. This test showed a flow rate of 0.68 L/s.

It is not believed that the flow rate varied much from run to run rather just the measure of the flow varied slightly due to the measurement procedures. Figure 4-1 shows that there is not a pattern of the flow rate slowing due to pump depreciation and usage as the values randomly surround the mean of 0.68 L/s.

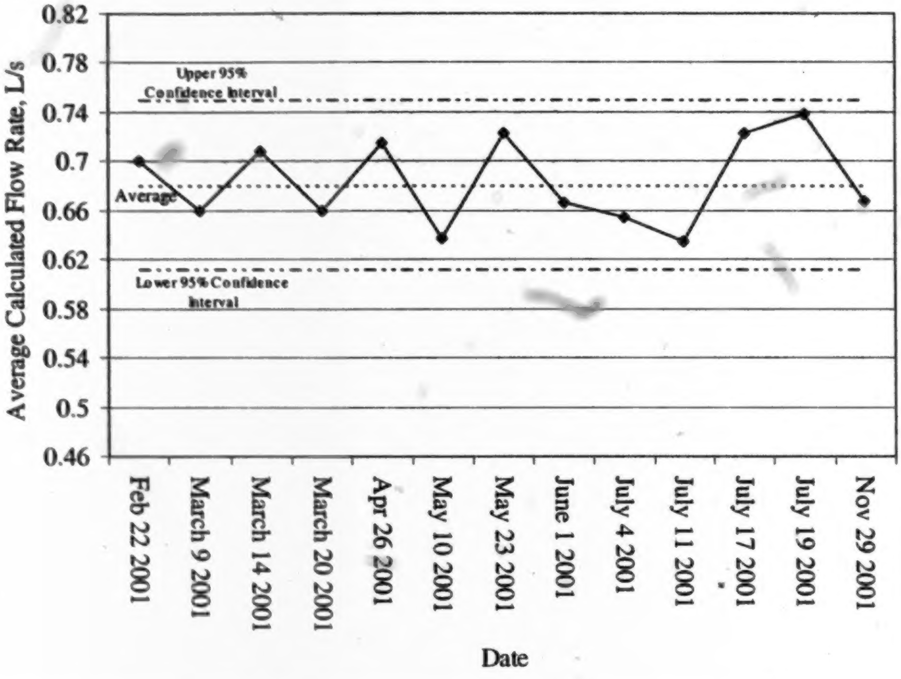

Figure 4-1 - Flow Rate Data

As such for all tests the flow was assumed to be 0.68 L/sec as this value fits with both the specific test for determining the flow rate as well as all the intermittent data collected throughout the data collection process.

4.1.2 Ozone Dose Determination

The results of the ozone determination test using the Indigo method showed that an ozone dose of 1.1 mg/L per pass. This test was a result of three separate trials at the beginning of phase 2 sampling and two in the middle of the phase two sampling. For the final two trials the ozone values were lower than determined during the initial trial. The major problem with the ozone determination was the delay in the addition of ozone from the venturi injector due to transport and start-up times from the ozone generator. Thus, variability existed in the ozone addition to the wastewater particularly on the first pass through the system (hence a tap water warm-up was used when testing samples). The ozone addition on subsequent passes was related to the time taken between passes to record data and recycle the wastewater from the holding tank to the process tank. This impact was not as large as that caused by the initial warm-up of the system. The volume of sample run through the test unit had an impact on the overall ozone applied to the system. This variability was mitigated by using large samples which reduced the impact of the start-up conditions. The sample volumes used for the O_3 experimentation were lower than those used during a typical test run (25 L, 15 L, and 15 L of indigo compared to a typical volume of 30 L of wastewater) therefore an intrinsic minor underestimation of the actual dose resulted. The magnitude of this under estimation was small. Table 4-1 shows the average results of duplicate indigo tests from the various test days and the various passes.

Table 4-1 Indigo Test for Ozone Results

	Test 1- March 9	Test 2 - June 1	Test 3 - June 1
Volume used (litres)	25	15	15
Ozone Applied mg O_3/L - Pass 1	1.1	0.5	0.5
Ozone Applied mg O_3/L - Pass 2	1.3	1.2	1.1
Ozone Applied mg O_3/L - Pass 3	0.85	0.86	0.64

These results show the “start-up” effect for pass one for tests 2 and 3 while for test 1 the start up effect was not as dramatic due to the larger volume used. The test unit, when operating with ozone, was warmed-up with ozone before the wastewater was introduced so the start-up effect would not be as significant during normal runs.

Therefore, the data from pass 1 are disregarded. The results from pass 2 show an average ozone application of 1.1 mg O_3/ L. Pass three results show lower amounts of ozone applied. It is believed that this is due to the indigo solution being discolored from the previous passes making further analysis of ozone applied to the indigo solution not accurate. Standard Methods (APHA, 1998) does not cite a maximum ozone dose measurable but after running the indigo through the test unit the third time the indigo had visibly changed its characteristic color from blue to a light green and therefore the results are questionable. For this reason the average values from the 2nd pass was used as the ozone dose for the test unit for each pass through the system. An average of 1.1 mg/L was found for these tests.

4.1.3 Salt Addition and Conductivity Change

The increase in conductivity from the addition of salt showed a small range of values in initial and final conductivity. This was not surprising as the initial conductivity of the wastewater was variable depending on the local conditions at the time of sampling. Also in working with large volumes of water getting the exact ratios of water to salt was difficult therefore the final conductivity shows a slightly wider range than that of the influent values. Figure 4-2 shows the conductivity increase of the water for all single pass runs with salt addition. It also includes the least squares fit trend line and the coefficient of determination (R^2). The data can be found in Appendix C.

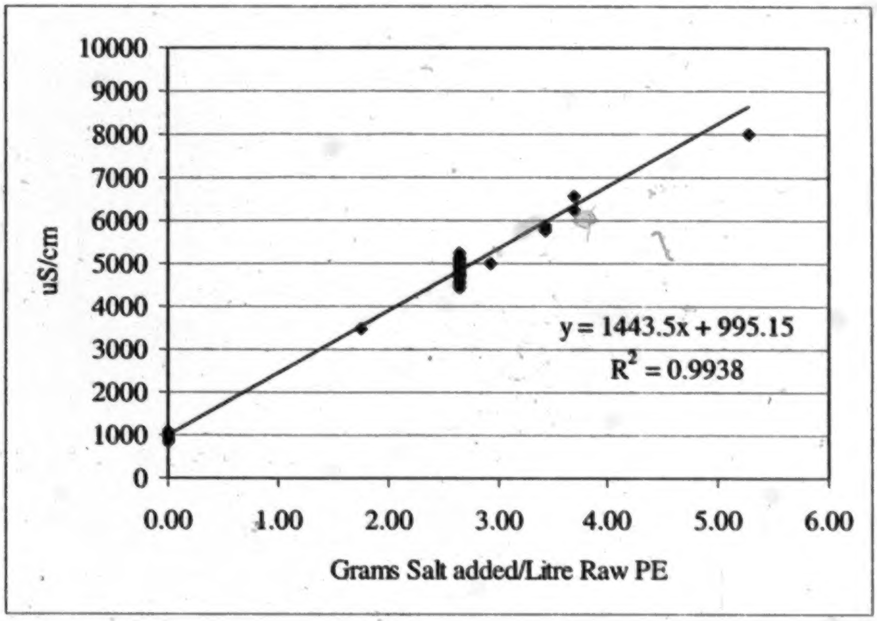

Figure 4-2 Conductivity vs. Salt added

Chen et al. (2000) suggested that an increase of 1 mg/L NaCl causes an approximate increase of about 2 μS/cm in conductivity at low NaCl concentrations for restaurant wastewater. This study saw lower values than Chen et al. (2000) with increases at 1.5 μS/cm for each mg/L salt added. Sawyer et al. (1994) suggest that the dissolved solids content can be determined by multiplying the specific conductance by a factor of 0.55 to 0.9 which yields a change of 1.11 to 1.82 times the mg/L salt added. Therefore the 1.5 μS/cm average increases per mg/L salt added obtained here was within the expected range. Sawyer et al. (1994) also suggest that the overall ionic components of a solution impacts the exact relationship and is specific to each water sample used. Under ideal conditions a linear relationship exists between the increase in salt and conductivity. However, it is expected that under non-ideal conditions, as higher concentrations of salt are added, the magnitude of increases conductivity drops.

Actual salinity was not measured in this study even though salinity can be easily measured it does not impact electroflocculation as directly nor as obviously as conductivity (Chen et al., 2000). Also, since relatively large volumes of salt were added manually the approximate amount of salt was already known.

4.1.4 Flotation Time Test Results

Although defining the precise flotation tank requirements and optimization of the flotation time and tank dimensions was not an objective of this study, a simple test on the impact of flotation time was under taken to yield approximate results on removal efficiencies. This information is important if the results taken from this project were to be used to evaluate much shorter flotation times. Initially, a 60 minute flotation time was used to allow flocs that were not captured by bubbles to settle out. However, when the sample collection procedure was changed (on March 2 which was prior to the majority of sampling) and sample was taken directly from the sample port rather than the holding tank all flocs were captured by bubbles and this eliminated the need for the long 60 minute flotation time. However, this time worked well with other operational timing so it was kept.

The flotation test was performed to see how the removal performance would be affected if shorter flotation times in the jar test container were used. Table 4-2 shows the removal efficiencies at different flotation times.

Table 4-2 Flotation Test Results

	TSS (mg/L)	COD (mg/L)	TP (mg/L)
PE	61	350	6.09
15min flotation	34	190	0.66
30min flotation	34	190	n/a
60min flotation	36	189	0.60
80min flotation	36	n/a	n/a
Test Code - 0704R3, Test Conditions included 2.64 grams / L Salt addition, With the Aluminum Electrode and Ozone			

These results show that no apparent change in parameter performance existed for TSS, COD and TP between the different flotation times.

This test was only run once and therefore there is not full confidence in these results however it does give the general idea that similar performance is expected at least at times as low as 15 minutes. Further investigation into the flotation process and the separations expected at different times with the Electroflоc^{PLUS} system would be of value especially to optimize sizing and performance of full scale electrofloc treatment plants.

This information is valuable because a potential advantage of Electrofloc^{PLUS} treatment is the small footprint of the unit. The sizing of the flotation tanks are directly related to the time required to get the desired separation. These flotation time test results show that the performance results discussed would be at least comparable to Electrofloc^{PLUS} treatment separations performed with shorter flotation times.

4.2 Preliminary and Phase 1 - Results

4.2.1 The MLSS Testing

The preliminary testing of sample involved running the test unit in its original configuration as seen in Figure 3-2. This phase was used to establish sample collection protocols and for learning the basics of the test units operation. The interesting points learned from this phase of testing will be discussed here.

The samples taken from the Goldbar WWTP during this phase was from a tap in tunnels underneath the treatment tanks. This source was said to be primary effluent by the operators at Goldbar WWTP. However, upon working with this source it was determined that the tap was not in fact primary effluent but probably a Mixed Liquor Suspended Solids (MLSS) from the activated sludge process. At first it was thought that the line was just clogged but attempts to "flush" the line by running large volumes of sample through it did little to improve the apparent "thickness" of the sample. The fact that this line was a MLSS was never formally confirmed by the Goldbar staff but in discussing the problem with a sampler from the City of Edmonton at the final PE sample collection site it was suggested that the initial line used was a MLSS.

This MLSS sample was tested using the Electrofloc^{PLUS} system with what appeared to be spectacular results. The flotation process of the test unit was capable of completely "lifting" this heavy waste to the surface. Percent reductions in suspended solids and COD were incredible but when considering them in terms of what was separated by just by allowing the sample to settle with no treatment the percent reductions beyond this are more in line with the results found from the true primary effluent. The important point being that the flotation process from the machine was capable of holding such heavy wastes on the surface. For example the test on Jan. 20, 2001 showed an initial TSS and COD of the MLSS to be 1483 mg/L and 1774 mg O_2/L respectively. After allowing this sample to settle on its own in an

Imhoff cone the relatively clear supernatant was tested and found the TSS and COD to be 55 and 268 mg/L, respectively. The 15 L sample after being run through the Electrofloc^{PLUS} test unit under its original batch configuration for 8 minutes and approximately 1100 Amps applied and it was completely floating. Sample taken showed TSS and COD values of 7 mg/L and 115 mg O_2/L, respectively. The total percent reductions seem impressive at 99.5% for TSS and 93.5% for COD but when considering that 96.3 % for TSS and 84.9% would be reduced by settling anyways these preliminary results become less impressive except for the fact that the process was completed in less than 15 minutes. The percent reductions beyond what occurs naturally are a more modest 87.3% reduction for TSS and a 57.1 % reduction for COD. Other samples tested with the MLSS showed similar values when taking into account the testing protocols used and salt additions.

The protocols for collecting sample from the machine and the machines operation was still in development at this point so the above results should be used as only a general idea of the machines capabilities on this type of waste stream and no inferences should be made as to the power consumption and economic viability of this process as this was not monitored at this point.

4.2.2 Batch Mode Testing

The test unit was configured into the single pass mode early (while still using the MLSS) in the experimentation with little initial success. Additionally, little was known in regards to the Electrofloc^{PLUS} performance with municipal wastewater so it was decided to attempt to run the unit in its original configuration until treatment with primary effluent could be seen and baseline levels established. This testing was an important component of the previously discussed iterative process in determining the test unit capabilities. The most important of these being the amount of salt required to bring the sample to a sufficient conductivity to run through the test unit. A summary of the pertinent results seen during this phase will be discussed. From Figure 4-3 it can be seen that at all the various conductivities tested that only those which were above 4000 µS/cm ever achieved the test units maximum amount of amps allowed (62 amps). It is also interesting to note that it was common to see amongst all the samples that a "warm-up" period existed before each sample reached its highest amps applied therefore for phase two testing a long warm up with tap water with the conductivity increased to the same levels used for the runs tested. Additionally it is interesting to note that at even highest conductivities the test unit was incapable of maintaining the high amps continually and it is very common to see high amps being applied and then having the amps drop temperately before returning to the high levels.

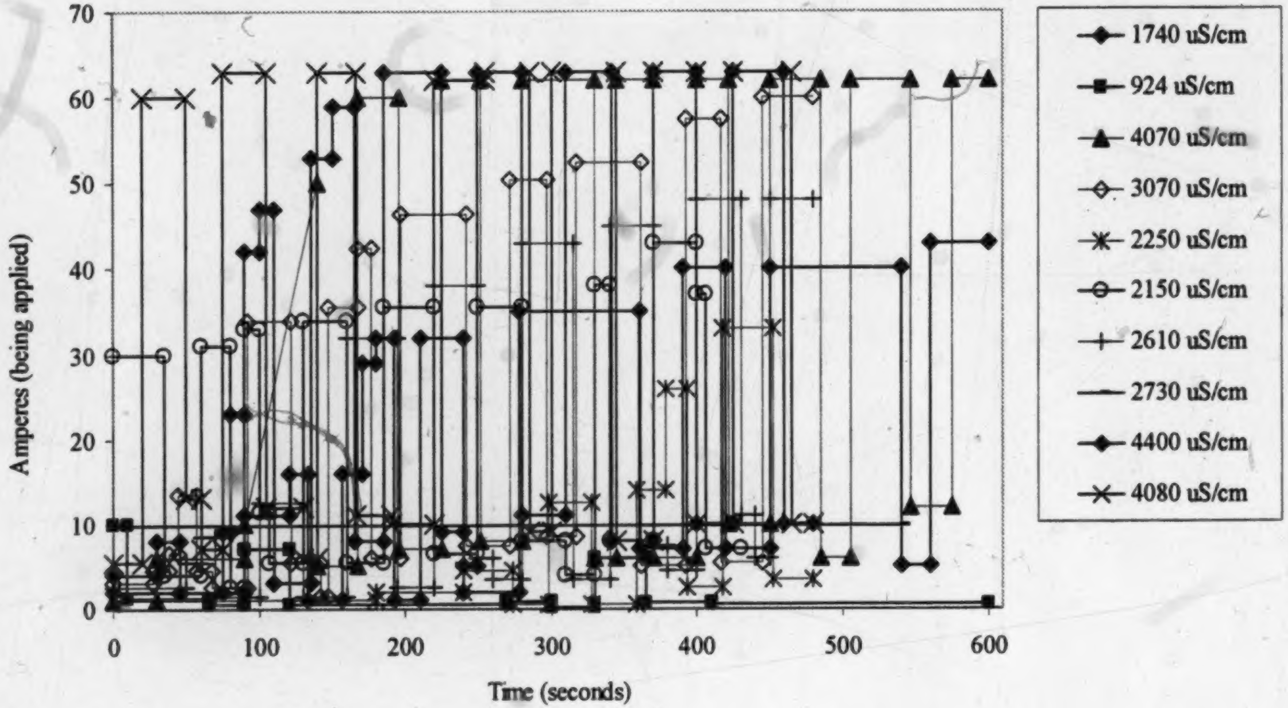

Figure 4-3 Amps Applied vs Time (all batch runs)

It appears, that from batch mode data that the Electrofloc^{PLUS} unit is in fact capable of treating wastewater at low conductivities and thus low amps but with more time through the electrochemical cell. With the test unit in batch mode numerous "recycles" could be used by simply increasing the batch exposure time and using less sample that could be recycled more times. The common problem with the data during this phase was extreme variability in the applied amps over the course of the 8 minute run. Figure 4-3 shows the major amperes applied record for the batch test runs and the time within the run and the conductivities used. Figure 4-4 shows the performance in terms of COD, TSS and were available phosphorus for the same wastewater samples with the data shown in Table 4-3. The percent reductions show that at the higher total amps applied treatment is occurring as the percent redections are significant. The time is determined by the length of time the test unit was run in batch mode while the volume is the volume used in the test unit for the batch run. The cycles through unit (equivalent) column was determined as the number of times the sample would have completely cycled through the system if run in single pass mode. This was simply determined by taking the total time of the batch run divided by the quotient of volume used for the batch run by the flow rate of the test unit (0.685 L / sec). As the following equation shows.

$$Cycles = \frac{TotalRunTime}{Time/Cycle} \tag{4-1}$$

$$\text{Where: } Time/Cycle = \frac{V\ /\ Cycle}{FlowRate} \tag{4-2}$$

The average amps was determined by taking a time weighted average of the amps applied. Average amps directly correlates with the area under each line graph in

Figure 4-3. The total amps applied is determined by multiplying the average amps by the cycles through unit (equivalent) column. The important note here is that typically 20 or more equivalent cycles through the unit was required to have sufficient amps applied to treat the water. The capture and recycling process used by the test unit when in single pass mode made treating low conductivities impractical as the process would have had to been repeated many times.

Table 4-3 Batch Test Results

Ave amps	Time (s)	Time(min)	Volume (L)	Cycles Through Unit (Equivalent)	Total Amps Applied	% TSS Reduction	% COD Reduction	% TP Reduction	Sample Conductivity	Notes
21.0	600	10	15.14	27.1	570	66.2	45.5	n/a	1740 uS/cm	
1.1	600	10	15.14	27.1	30	0.0	23.5	n/a	924 uS/cm	
32.0	600	10	15.14	27.1	869	55.0	45.1	n/a	4070 uS/cm	
26.6	480	8	15.14	21.7	577	89.7	56.5	n/a	3070 uS/cm	
5.9	480	8	15.14	21.7	129	39.6	51.1	57.1	2250 uS/cm	No Ozone
20.0	430	7:10	15.14	19.5	390	71.7	58.4	84.1	2150 uS/cm	
19.5	480	8	15.14	21.7	423	89.8	60.7	91.3	2610 uS/cm	
9.8	540	9	15.14	24.4	239	0.0	19.3	24.0	2730 uS/cm	
31.4	480	8	18.93	17.4	546	75.0	59.2	94.1	4400 uS/cm	No Ozone
38.8	480	8	18.93	17.4	674	73.3	59.5	95.3	4080 uS/cm	

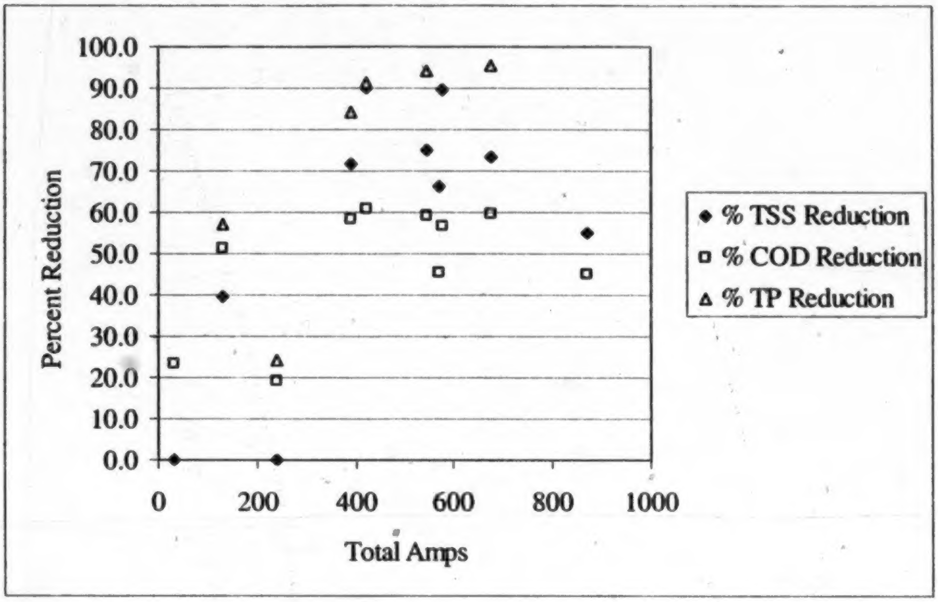

Figure 4-4 Performance Batch Runs

To summarize the batch mode, testing shows that high conductivities were required to illicit the full amps that the test unit was capable of providing. However, these results also show that the unit was capable of treating low conductivity water if given a long enough exposure to the electrochemical cell. The problem being that under low amps applied for a longer time period other (non-electrochemical cell) operational costs and capital costs would have to be increased when compared to using the maximum amps desired for treatment. Multiple electrochemical cells would be required or recycling would be necessary. This would result in increased pumping costs, increased space requirements and/or increased infrastructure requirements. Additionally, the batch mode by its nature created data which was difficult to interpret clearly especially in terms of how the system would operate in full scale operation. It should again be noted that during the batch mode operations many procedures were still in development and therefore these results should be considered as guide rather than being definitive.

4.3 Phase 2 Testing Results

4.3.1 Process Variability in the Applied Amperes

The protocols used to prevent variability (discussed in section 3.4.3.1) significantly reduced the process variability so that by the time the phase two testing began (after running 6 single pass runs and 15 batch mode runs) the unit process variability had been significantly reduced. However, variations as large as 10 to 62 A applied could be found both within individual passes through the system (i.e. the start of the pass 62 A are recorded but sometime during the run the amperes applied jumps to 10 A and then possibly back up 62 A again) and between different passes (i.e. pass 1 applies and average of 62 A while pass two records an average of 10 A) even after the consistent and best protocols were developed.

From the phase 1 single pass tests it was observed that variability seemed to be somewhat connected to the testing conditions (i.e. ozone vs no ozone). To establish if the variability problem was more significant under different conditions qualitative and quantitative records were kept and analyzed to give an idea of the frequency and significance of the variability of the power supplied under different conditions. Figure 4-5 summarizes the average amperes applied and the variability records for the amperes applied for all single pass test runs with a salt addition of exactly 2.64 g/L.

The measures used on Figure 4-5 will be explained here. The average amperes section on the table represents the average amount of amperes applied per pass for a test run. For example if the test run had 3 passes and pass 1 gave 10 amps, pass 2 gave 11 amps and pass 3 gave 9 amps then the average amps for that run would be 10 amps. The standard deviation represents the associated standard deviation for the same data as discussed for the average amps (i.e. using the example of the test run with 3 passes with pass 1 yielding 10 amps, pass 2 yielding 11 amps and pass 3 yielding 9 amps the standard deviation would be 0.8 A).

The smaller the standard deviation the less spread out the data are meaning that smaller the standard deviation the more likely each pass during a test run yielded similar amps.

The percent consistent within section of Figure 4-5 shows the percentage of passes in which the amperes displayed during the pass only changed within in a range of ± 4 amps for the majority (95% or greater) of the time as the wastewater passed through the test unit. The test unit has a tendency to change the amps applied suddenly from one level to another level during its operation. For example during a pass while the water is flowing it might suddenly change from 60 amps to 20 amps and stay there for say five seconds and then return to 60 amps. Occasionally it would not return to the higher value for a long time and when this happened the pump would be stopped in the middle of the pass the breakers reset and then the pass would be finished usually allowing the ampere applied to get back to the original level. This example would be recorded as not consistent amps for the run. On other occasions a less common but still regular occurrence was the test unit to say start at 30 A and then gradually climb to 60 A over the course of a run this too would be recorded as an inconsistent run. When these events occurred the length of time spent at each ampere level (or the time taken to gradually increase) was recorded and then the recorded values were time weight averaged to determine the amps applied over the entire pass which then becomes one of the individual pieces of pass data used to calculate the average amps (as discussed earlier) for the entire test run which is composed of multiple passes (usually 7 passes or 11 passes). Another example includes the unit starting at around 59 A slowly moving to 62 A then suddenly back to 59 A applied and staying near that value for the remainder of the run. For this example the ampere data for the pass would be estimated at the average point in-between those values (59 and 62 A) and since it did not vary ± 4 amps this run would be recorded as a "consistent" run. Keeping and recording these values was difficult to do as some judgment was required to make the estimations. The data for Figure 4-5 can be found in the Appendix D.

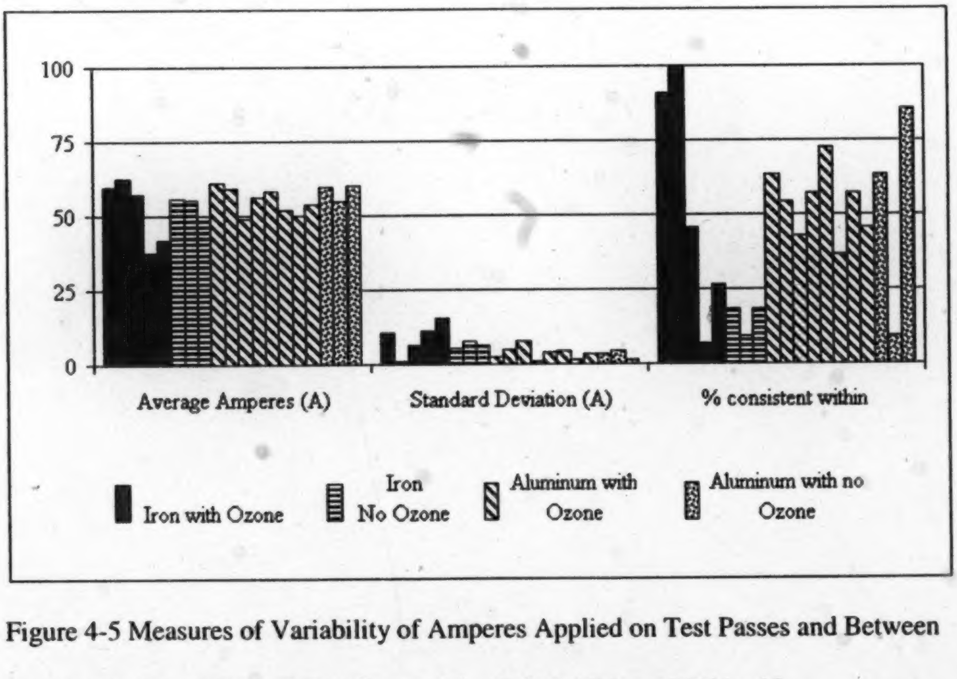

Figure 4-5 Measures of Variability of Amperes Applied on Test Passes and Between Test Passes for all Phase 2 Test Runs with a Salt Addition of 2.64 g / L.

This figure shows that the test unit operated with approximately the same average amperes applied and the same process variability under the different testing conditions both within and between passes. For the percent consistent it looks like the ozone trials are generally lower as well (4/6 test runs are below 25% consistent without ozone while only 1/13 test runs with ozone are below 25% consistent). Physical experience working with the test unit at all conductivities used suggested the unit operated less effectively (highly variable) without ozone addition although the operator remembers this impact as being more distinct than what is seen by the recorded data. It is important to remember that the collection of the data for Figure 4-5 required a large degree of operator judgment/estimation and as such there is inherit uncertainty as to the accuracy of data and the reproducibility of these data when conducted by a different operator.

4.3.2 Factorial Design Conditions and Considerations

This section analyses the results from testing runs starting March 7, 2001 (0307R1) in which the unit's operational settings were varied from using the iron electrode and aluminum electrode and operating with ozone application via the venturi and without ozone application (air is injected through the venturi). At the start of this analysis the operational and sample collection procedures had been fully defined and the parameter analytical methods were well developed. As a guide for the testing a factorial arrangement was used. To analyze the data a factorial design was also employed. To expand further on what was seen from the factorial design basic data chart plots and visual analysis was used in combination with more complex statistical methods including regression and ANCOVA (analysis of covariance).

As discussed in section 3.2.1 the factorial design has some major advantages in the use of factorial designs in that they are capable of determining two and three factor interactions. That is it can be used to identify potential synergistic effects between different testing conditions (Box et al. 1978). The factorial design was run with complete triplicate analysis. That is the entire treatment process was replicated three times right from the start including the sample collection phase, the treatment phase and parameter analysis phase were all undertaken independently for each of the three replicates in order to gain true measure of total variance from the full process and not analytical variance (Box et al., 1978). As such the test runs used as part of the overall factorial design include those summarized in Appendix F. The ozone and electrode settings along with the amperes applied and all of the water quality parameter data for TSS, COD and TP for these runs is summarized there. The data analysis methods used here can be found in Box et al. (1978) as this reference provides additional detail about Factorial Design methods. For this study a complete triplicate 2^3 factorial design was used.

The following table shows the conditions for the factorial design set-up.

Table 4-4 Factorial Design Setup

Factor One	
Name	*K(electrode)*
Low (-)	*A (Iron)*
Hi (+)	*B (Aluminum)*

Factor Two	
Name	*C(ozone dose)*
Low (-)	*No*
Hi (+)	*Yes*

Factor Three	
Name	*T(amps applied)*
Low (-)	*45 to 60 (A)(1 pass)*
Hi (+)	*350 to 430 (A)(7 passes)*

The first factor was electrode. The second factor was whether or not ozone was injected through the venturi injector (if no ozone then room air was injected). The third factor was the most difficult of all to assess. The amps applied actually refers to passes through the system at 7 passes for the high value and 1 pass for the low value. The amps applied values shown simply refer to the amperes applied range after 7 passes for the 12 runs used for this factor. The ampere range indicated for 1 pass is indicative of the amperes applied range experienced for the 12 runs used for this factor. The use of passes for this step of the analysis rather than amps is due to the inconsistency of the amperes applied (i.e. amps are inconsistent but passes can be held constant so any factor that creates the ampere inconsistency would also impact the pollutant removals which the definition of is ultimately the goal of this part of the data analysis).

No pattern was seen between the average amps applied and the different conditions used (Figure 4-5 shows this and was discussed earlier). Therefore, the amp range was used for discussion purposes rather than the number of passes as it was the major factor involved and was for the most part consistently applied. Also, the factorial design was run in triplicate to balance out the random ampere applied variance.

For the graphical data analysis methods and descriptive methods used later in this document the amperes applied can be directly used as each specific ampere applied value can be assigned to a specific value. If the Electrofloc^{PLUS} power supply was capable of providing consistent amperes then amperes applied could have been used for the factorial design and it would have made the remaining analysis much easier.

All of the studies were conducted with the ozonated vs. unozonated samples paired to a specific wastewater which means all conditions for the ozone vs. unozonated samples for a particular wastewater were identical and this eliminated unwanted sources of variability in comparing the samples. Of course, in statistics when something is gained something else is lost. In this case by reducing unwanted sources of variability with the ozone addition impacts it creates confounding patterns that will be discussed later in this section.

To compensate for changing wastewater conditions between replicates percent reductions were used rather than direct performance for the factorial design analysis. Additionally, the use of percent reduction also diminishes the confounding impacts of using different blocks (different wastewater samples used for different test conditions within the same replicate and in this study all tests run with the iron electrode were blocked and all tests with the aluminum electrode were blocked to a specific source wastewater). The use of blocks was required because it was not possible to collect enough sample from one collection for all eight conditions of one replicate nor would it be possible to do enough test runs in one day to complete all eight conditions required for a single replicate of the 2^3 factorial design. Additionally, it was neither practical nor desirable to collect a separate random wastewater sample for each of the 8 conditions. Therefore, blocking was necessary which causes losses of true randomization and creates confounding impacts from lurking variables associated with the difference in the blocks. Ideally a blocking arrangement for a 2^3 factorial can be setup so that each blend is run at opposite ends of the design cube. In Figure 4-6 the 28.1, 44.8, 19.1, and 68.1 would be a block the others values would be the other block (Box et al., 1978). In this arrangement the only three factor interaction is confounded with the blend difference and this interaction is usually unimportant. Unfortunately this arrangement was also not possible because switching electrodes after one pass would not have allowed the continuation of the run to the high level of treatment under similar conditions. Of course switching electrodes was physically possible but it would have created a different treatment condition (i.e. one pass iron, six passes aluminum). This parameter would have to be incorporated into the design making the design a larger factorial. The impact of passes through differing electrodes throughout a run was not examined in this thesis. Because the blocking arrangement was necessary and had to be performed with the points not on opposite ends of the cube seen in Figure 4-6, the electrode type/ozone dose interaction and the electrode type/amperes applied interaction are confounded with the blend effect caused by the different wastewaters.

Running the test in triplicate itself however lowers the likelihood that the two two-factor interactions is indeed due to the blocking as different wastewater condition make it less likely that all of one particular condition received a "bias" wastewater every time. The confounding impact of blocking was not great because the interaction effects that were confounded were not found to be significant.

4.3.2.1 TSS Example

As TSS is a guide to the over strength of a wastewater this parameter will be discussed first. The analysis was preformed according to methods outlined by (Box et al., 1978). Table 4-5 gives the experimental factors and the associated TSS percent reduction response.

Table 4-5 Experimental Factors and Responses

Treatment Number	**Factors**			**Response(% TSS Reduction)**		
	K(electrode)	***C(ozone dose)***	***T(amps applied)***	**Rep 1**	**Rep 2**	**Rep 3**
1	*A (Iron)*	*No*	*45 to 60 (A)(1 pass)*	*21.7*	*22.0*	*22.3*
2	*A (Iron)*	*No*	*350 to 430 (A)(7 passes)*	*41.0*	*37.1*	*56.3*
3	*A (Iron)*	*Yes*	*45 to 60 (A)(1 pass)*	*17.1*	*30.1*	*10.2*
4	*A (Iron)*	*Yes*	*350 to 430 (A)(7 passes)*	*59.0*	*59.6*	*55.3*
5	*B (Aluminum)*	*No*	*45 to 60 (A)(1 pass)*	*47.7*	*31.1*	*5.6*
6	*B (Aluminum)*	*No*	*350 to 430 (A)(7 passes)*	*79.4*	*58.5*	*45.8*
7	*B (Aluminum)*	*Yes*	*45 to 60 (A)(1 pass)*	*63.6*	*34.0*	*9.7*
8	*B (Aluminum)*	*Yes*	*350 to 430 (A)(7 passes)*	*85.0*	*62.3*	*56.9*

The calculation of the main and interaction effects was performed. Table 4-6 presents the calculation matrix as well as the resulting main effect estimates and the interaction effect estimates.

Table 4-6 Calculation Matrix and Resulting Main Effect and Interaction Effect Estimates

Treatment Effect Vectors					**Interaction Effect Vectors**				**Response**	
Number	***Mean***	***K(electrode)***	***C(ozone)***	***T(amps applied)***	***K * C***	***K * T***	***C * T***	***K * C * T***	**Means**	**Vars**
1	+	-	-	-	+	+	+	-	22.00	0.09
2	+	-	-	+	+	-	-	+	44.80	102.99
3	+	-	+	-	-	+	-	+	19.13	102.10
4	+	-	+	+	-	-	+	-	57.97	5.42
5	+	+	-	-	-	-	+	+	28.13	449.70
6	+	+	-	+	-	+	-	-	61.23	287.84
7	+	+	+	-	+	-	-	-	35.77	728.64
8	+	+	+	+	+	+	+	+	68.07	222.34
Effect Est.	42.1	12.33	6.192	31.76	1.042	0.942	3.808	-4.21	**Pooled Variance**	
Effect SE	3.145	6.29	6.29	6.29	6.29	6.29	6.29	6.29		237.39

From Table 4-6 it can be seen that only the amperes applied (passes) and electrode used were significant (i.e. they exceed the standard error). On the other hand the ozone dose was close to its standard error so that this main effect may indeed also be significant in the reduction of TSS. As a check of the above a normal probability plot and a comparison to a reference *t*-distribution was used to confirm these finding and can be found in Appendix G. Box et al. (1978) provided a discussion on the use of normal probability plots. No significant interaction effects were found using this analysis. Therefore, the study reserves judgment that no interaction effects exist and that the differences were most likely caused by random noise. The data show's however that the ozone dose / amperes applied interaction would be the most likely two-factor interaction possible and this factor interaction is not confounded with blend effects as discussed earlier. Further research is required to investigate if this interaction actually exists.

The factorial design for TSS percent reductions used in this study did yield valuable information. Figure 4-6 shows the average percent reduction as a box diagram to visually show the average changes. Each corner on the box represents the different test conditions as given in Table 4-4.

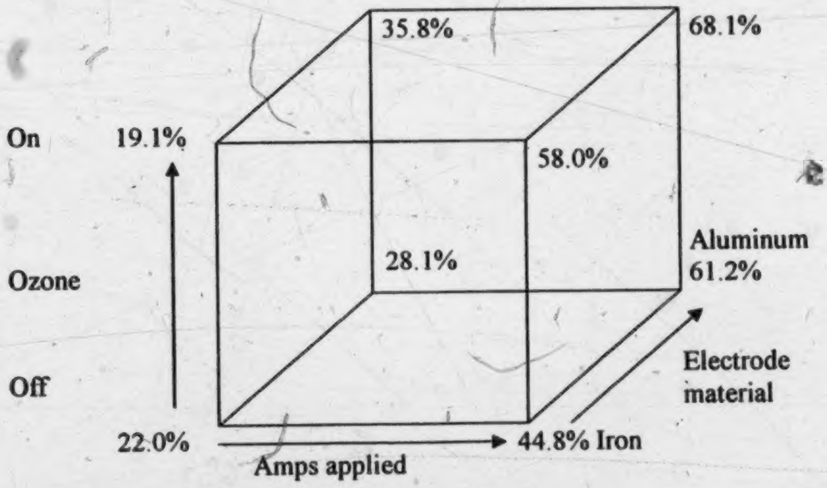

Figure 4-6 TSS Factorial Design Average Percent Reductions

From this it can seen that the best conditions are high amps applied, ozone on and aluminum electrode. The effect of high amps (7 times through the system) is to increase the percent TSS reduction by 31.8 % (see Table 4-6 for calculation matrix). While the overall effect of using the aluminum over the iron electrode is to improve percent TSS reduction by 12.3% (see Table 4-6 for calculation matrix). These values can be interpreted individually because they show no significant interactions effects exist with other variables. The box diagram also shows the general trend of increasing performance with ozone dose applied, electrode material, and amperes applied even though the ozone dose was not consider statistically significant. This was not surprising as the literature discussed earlier would for the most part confer with these findings.

4.3.2.2 Factorial Design – Other Parameters (TP, COD)

The same factorial process used above was used to determine what was happening with COD and TP. Table 4-7 shows the results of the analysis. Remember the units used are percent reduction rather than absolute values. It also includes the aforementioned TSS results for comparative purposes. Box diagrams can be found in Appendix G along with the calculation matrix, resulting main effect, and interaction effect estimates table. The experimental factors and results table along with the normal probability plot checks on the determined significant effects are also provided.

Table 4-7 - Factorial Design Results (TP, COD and TSS Percent Reduction)

TP - Effects and Standard Errors		
Effect	Estimate	SE
Mean	70.25	2.41
K(electrode)	-3.68	4.82
C(ozone dose)	9.84	4.82
T(amps applied)	41.33	4.82
K * C	-1.13	4.82
K * T	7.35	4.82
C * T	-6.69	4.82
K * C * T	-1.33	4.82

COD - Effects and Standard Errors		
Effect	Estimate	SE
Mean	44.95	1.35
K(electrode)	2.75	2.70
C(ozone dose)	4.08	2.70
T(amps applied)	12.87	2.70
K * C	1.57	2.70
K * T	1.38	2.70
C * T	-4.82	2.70
K * C * T	-2.00	2.70

TSS - Effects and Standard Errors		
Effect	Estimate	SE
Mean	42.14	3.15
K(electrode)	12.33	6.29
C(ozone dose)	6.19	6.29
T(amps applied)	31.76	6.29
K * C	1.04	6.29
K * T	0.94	6.29
C * T	3.81	6.29
K * C * T	-4.21	6.29

For TP the main factor impacting performance was the amperes applied (passes). With more amps applied, the better the treatment is, as 41.3% reduction increase overall was seen when moving from the low treatment to the high treatment. For phosphorus the ozone dose was found to be significant. The electrode material was not a significant main effect.

The interesting note about phosphorus reduction is according to the factorial analysis, the electrode type on it own has no significant impact on the treatment process. The electrode/amperes applied two-factor interaction however was significant therefore this suggested that as the treatment level increased the electrode selection becomes more important in improving removals, while the initial removal of phosphorus will be similar regardless of electrode selection. It is important to point out here that this interaction effect may be due to blend confounding as discussed for the TSS although for reasons already pointed out this was less likely and a true interaction was seen.

The ozone dose/amps applied two-factor interaction also exceeded the standard error but it was still pretty close to the standard error so the judgment will be reserved as to it's significance. If it the interaction was actually significant it would indicate that as low amps move to high amps the ozone dose has less of impact on improving process performance (-6.7% when compared to its impact at the low amps). Perhaps performance could be optimized by using ozone at the beginning of the run as the dose has a significant positive impact on performance and switching to air nearer to the end as the amps applied/ozone interaction shows that the ozone had diminishing returns in performance at the high amp level. This could only be done in full scale flow regime set up in series as the Electrofloc^{PLUS} test unit used simulated. The ozone dose/amps applied two-factor interaction was not confounded with the blend blocking.

The COD factorial design results will now be discussed. Not surprisingly the amperes applied was the main effect for the reduction of COD. However it was significantly lower as a move from around 52 A (1 pass) to around 380 A (7 passes) only improves the reduction percent by 13. The only other main effect that exceeded the standard error was ozone dose which was very close to the standard error meaning that judgment was reserved as to its significance.

Like the total phosphorus the ozone dose/amps applied two-factor interaction exceeded the standard error and may have been significant and was once again negative. (i.e. at low amperes applied the ozone presence had a large impact on the reduction of COD whereas at higher amperes applied the ozone became less of a contributing factor.) The same arguments given above could be used that perhaps use the ozone at the beginning of a series and then curtailing the addition towards the end of the series would allow for cheaper operational costs while not greatly hurting performance.

4.3.2.3 Factorial Design Final Considerations

What was found from the factorial design results was first the obvious that additional passes of a wastewater through the test unit and the resultant additional amperes applied cause significant (0.05 level) improvements in pollutant reductions for all water quality parameters. The use of aluminum instead of iron seems to have its greatest impact on TSS as it is a significant factor (0.05 level) for this parameter resulting in a 12.3% TSS reduction improvement across the different treatment conditions. The electrode material main effect on COD and TSS is much less pronounced and does not significantly exceed the standard error for these variables. The addition of ozone as a main effect does not appear to be a major contributing factor except for phosphorus where it caused a significant (0.05 level) improvement by causing an increase in percent reduction by 9.8 % across all conditions.

The interesting potential interaction effect seen was the ozone / amperes interaction, as evidence suggests that for the total phosphorus and the COD a relationship may exist (is significant at 0.1 level but not at the 0.05 level). This relationship shows that as the number of passes increased the benefit of the ozone was diminished. Also, by visual inspection of the box diagrams it can be seen that generally speaking the reduction performance was the best with the aluminum electrode with ozone with higher passes even if this was not always statistically significant in the factorial analysis. The box diagrams found in Figure 4-6 for TSS and in Appendix G for COD and TP clearly shows this.

The factorial design was a logical way to view and analyze data with three separate variables and gave excellent insight and screening analysis for further testing and how the bulk of the data should be analyzed and viewed. It also gave an experimental setup that ensures consistent testing and replicating testing across the different variables thought to impact performance. The factorial design does not consider curvature in moving from one variable to the next and as such only defines relative change and not the absolute effect a variable such as the addition of amperes applied. It is known that the performance for most parameters due to additional amps applied does indeed show curvature. In this case it is a decreasing improvement type curve over all amperes applied. If the performance of the unit were to cause a decrease in a parameter and then a subsequent increase of the parameter after some point of treatment and this point was selected in the factorial design then the factorial would be of no value (this was actually seen with ammonia and will be discussed later but was not seen in the parameters used in the factorial design). So how are the best settings determined? Multiple data points are required and were also sampled so that performance curves could be identified. To this end the following section will analyze the best fit curves collecting data at 1 pass, 3 passes, 5 passes, 7 passes and 11 passes for the different parameters shown using the same test runs that were conducted as part of the factorial.

4.3.3 Expanded Analysis of Tests Performed Under Different Conditions

This analysis will go beyond factorial design method to further explore process efficiencies and help to develop an inference into what are optimal process settings so that further test runs and parameter analysis can focus on these settings. A performance standard can then be determined with the given electrical inputs and can be proven under the operational procedures used. As full process triplicates were used the variation seen here is indicative of total process variation and not just analytical variation. The test runs used for this analysis are the same ones as discussed in section 4.3.2.

4.3.3.1 Variables Used for Analysis

The typical x variable (the abscissa ordinate) is amperes applied and in the remaining analysis it is actually amperes applied and not passes through the system (as used in the factorial design) because the precise ampere applied measurement can now be used with the statistical methods. In this expanded analysis the precise amperes applied is used as it is felt to be a better indicator of expected performance than is straight passes (i.e. the treatment level expected is most dependant on the amperes applied). The problem was being able to maintain consistent amperes applied during runs with identical conditions to keep consistent testing protocols. When considering these results the reader is reminded that with increasing amperes applied the wastewater is also being also exposed to relative increases in other conditions (such as more mixing, greater exposure time to ozone, greater cumulative ozone dose, greater exposure time in the electrochemical cell, etc.) that also increase in an approximately upwards correlation with the amperes applied depending on the supply of amperes on any given pass. If the unit had more driving volts changes in amperes applied could have been conducted independently of increased passes as 400 amps could have be applied in one pass rather than 7. Also the potential of the salt addition impacting performance could have been avoided.

For the ozone dose in the above factorial design analysis it is reported as "on" and "off". The actual measure is ozone/pass. That is the low value is 0 mg/L /pass while the high value is 1.1 mg/L / pass (as determined in section 4.1.2). When considering the ozone dose in comparison to the amperes applied (for the expanded analysis section to follow) it becomes a bit more complex and is modeled as ozone dose per ampere applied and can be approximated based on the average amperes applied. Amperes applied has shown the greatest impact on parameter performance and specific amperes applied values are used for all further analysis in this paper while only the approximate relationships are assumed for ozone dose using its relationship to the amperes applied to simplify related calculations. Because the overall impact of ozone dose was small relative to the amperes applied the error in this assumption would also be very small. For example at 7 passes a range of 350 to 430 amperes applied was experienced for the factorial design runs. In terms of overall treatment a difference of 80 amps is significant as amperes applied was shown by the factorial design to be the most important main effect under the same conditions. (i.e. passes used as a performance indicator rather than total amperes applied). The ozone dose is the same for all amperes levels at the 7 pass limit (350 to 430 A applied) regardless of the amperes applied and therefore the 350 A should show better relative performance when ozone was added than for a run when no ozone was added. The factorial design (which technically used passes rather than amperes applied) showed that between ozone dose and amperes applied that overall ozone addition had relatively little effect compared to the amperes applied. Therefore, it is concluded that small differences in the actual amount of ozone applied 0.018 (mg O_3 /L)/ A to 0.022 (mg O_3 /L)/ A at the max and minimum amperes would not result in significant errors in terms of the parameter performance difference. The following calculation determines the ozone dose per ampere applied.

$((1.1 \text{ mg } O_3/L)/\text{pass})*(7 \text{ passes}) /350 \text{ A} = 0.022 \text{ (mg } O_3 /L)/ \text{ A applied}$

As the significance of the ozone is small relative to the amperes applied throughout the remainder of this theses amperes applied is modeled as the only independent variable even though ozone and amperes applied could be modeled as separate independent variables with cumulative ozone dose being one variable and cumulative amperes applied being the other. The statistical complexity of such analysis would be much greater and thus would yield results more difficult to understand. This loss in simplicity is not made up for by the greater accuracy as the error associated with the assumption is very small. Since Table 4-5 shows an approximate average amperes applied of 55 amperes/pass for aluminum with ozone samples with a range between 48 amperes/pass and 61 amperes/pass for the aluminum with ozone samples in future analysis an ozone dose of 0.02 ± 0.003 (mg/L)/(Ampere applied) was assumed. Table 4-8 relates the approximate cumulative ozone dose to the cumulative amperes applied and can be used to determine the approximate cumulative ozone dose at any given ampere applied level. The table was created by using the average amperes applied at each pass level for the test runs 0307R1, 0307R2, 0312R1, 0312R2, 0314R1, 0314R2, 0510R1, 0523R2, 0709R1, 0709R2, 0711R1, 0711R2, 0713R1, 0713R2, 0717R1, 0717R2, 0719R1 and 0719R2. The raw ampere applied data for these runs is found in Appendix A. The actual cumulative ozone doses at any given number of passes for any specific test in question can be determined using that data.

Table 4-8 Ozone Dose to Amperes Applied Amps Comparison

Passes	Average Cumulative Amperes Applied	Cumulative Ozone Dose (mg/L)	Dose (mg/L) / per Ampere applied
1	53	1.1	0.021
3	162	3.3	0.020
5	273	5.5	0.020
7	388	7.7	0.020
11	627	12.1	0.019

As side note to this table the slight decline average ozone dose is a result of improved amperes applied (on average more amperes were applied per pass on latter runs than earlier runs) over the course of a test.

4.3.3.2 Total Suspended Solids (TSS)

In visual inspection of the total suspended solids data for the units operation reveals that a large variation exists especially for the ozonated aluminum electrode samples. As such finding a suitable best fit equation to define the data was difficult. Figure 4-7 shows a scatter plot of all the TSS data.

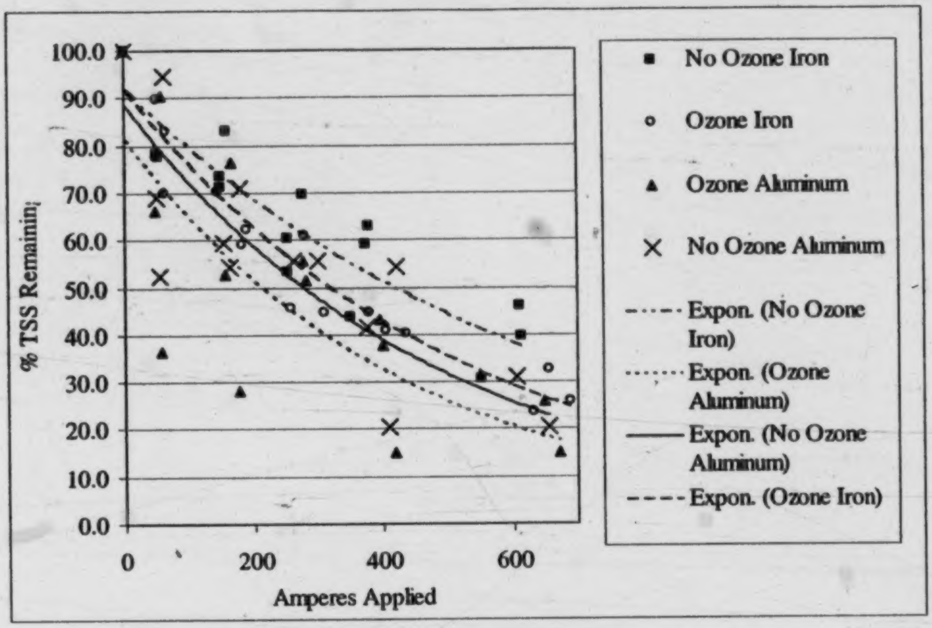

Figure 4-7 TSS Percent Remaining Scatter Plot with Best Fit Lines

From this scatter plot it can be seen that data follows a rough linear decline in performance with the ozone aluminum combination. Using Microsoft Excel computer software a number plots were fit to explore what regression equation would best fit the data. From this the following table was made.

Table 4-9 R Square Values for Fitted Lines

	R Square			
	Log	Power	Exponential	Linear
No Ozone - Iron	0.7573	0.6154	0.823	0.8192
No Ozone - Aluminum	0.7365	0.5669	0.7561	0.7314
Ozone - Iron	0.8092	0.6734	0.9403	0.8697
Ozone - Aluminum	0.7105	0.5426	0.6508	0.6217

With values closer to 1 the better the variation of the data is explained by the trendline used (Burt and Barber, 1996). As can be seen the exponential curve fits most of the data best. However, for the Aluminum with ozone test the variation tends to be explained better by a natural logarithmic equation. This is significant in that for TP and COD as we will be discussed later also fit this equation quite well.

It is important to remember that r square does not in fact imply that a trendline is significant, it is just a measure of how well the variation of the data is explained by the regression equation. To determine the whether a trendline is significant typically a t-test is employed for one independent variable (simple linear regression) while the F-distribution is normally used in test cases involving multiple independent variables (multiple linear regression). Tests for significance of trendlines were conducted using the 'Regression Analysis' function in Microsoft Excel Computer Software and can be found Appendix H. It is also important to note that analysis of residuals is critical in determining model fit (Box et al. 1978). A random distribution of residuals shows that model is a good fit a patterned distribution may indicate other trends (Burt and Barber, 1996). Residual plots are also found in Appendix H.

In terms of what can be seen from Figure 4-7 is similar to what was learned in the factorial analysis. In that amperes applied plays the major role and electrode selection plays a secondary role. The role of ozone from the plot again shows that it may indeed be of some value but it is unclear do to the large amount of scatter. Despite the poor fits of all the models they were graphed with an exponential best fit line (a normal linear regression with the y-axis values log transformed, (Middleton, 1997)) so that a non-visual confirmation (i.e. a mathematical confirmation) of the above could take place.

It is important to remember that lines are not suggested to define the performance but rather indicate the most typical comparative reductions at various amperes applied based on the evidence available. Figure 4-7 shows the trendlines. The equations are not shown as the lines are not suggested to represent expected performance. The best fit exponential trendline shows that overall the electrode type has the biggest impact on performance while ozone appears to have a secondary impact albeit it is not necessarily significant.

An ANCOVA statistical test was performed to see if there was a significant difference between the iron electrode with ozone treated samples and the aluminum electrode with ozone treated samples. The ANCOVA test showed that there was no statistically significant difference (0.05 level, a p-value of 0.147 was found meaning it would be significant at the 0.15 level) between the TSS percent reduction (dependant variable) of the two systems. An ANCOVA analysis comparing aluminum electrode with ozone to aluminum electrode no ozone found no significant difference between systems (0.05 level, a p-value of 0.328 was found).

4.3.3.3 Total Phosphorus

This section will define phosphorus removal under different conditions. Figure 4-8 on the follow page shows the best fit curves and scatter plot data of four test conditions.

Through visual inspection (of the x y plot and the residuals) it was found that the best fit trendlines for percentage remaining phosphorus were intrinsically linear and a natural logarithmic transformation was used for a fitting adjustment. This fit works very well for the samples with ozone addition (residuals show no pattern) but for those without ozone there were large residuals from the best fit curves at the 50

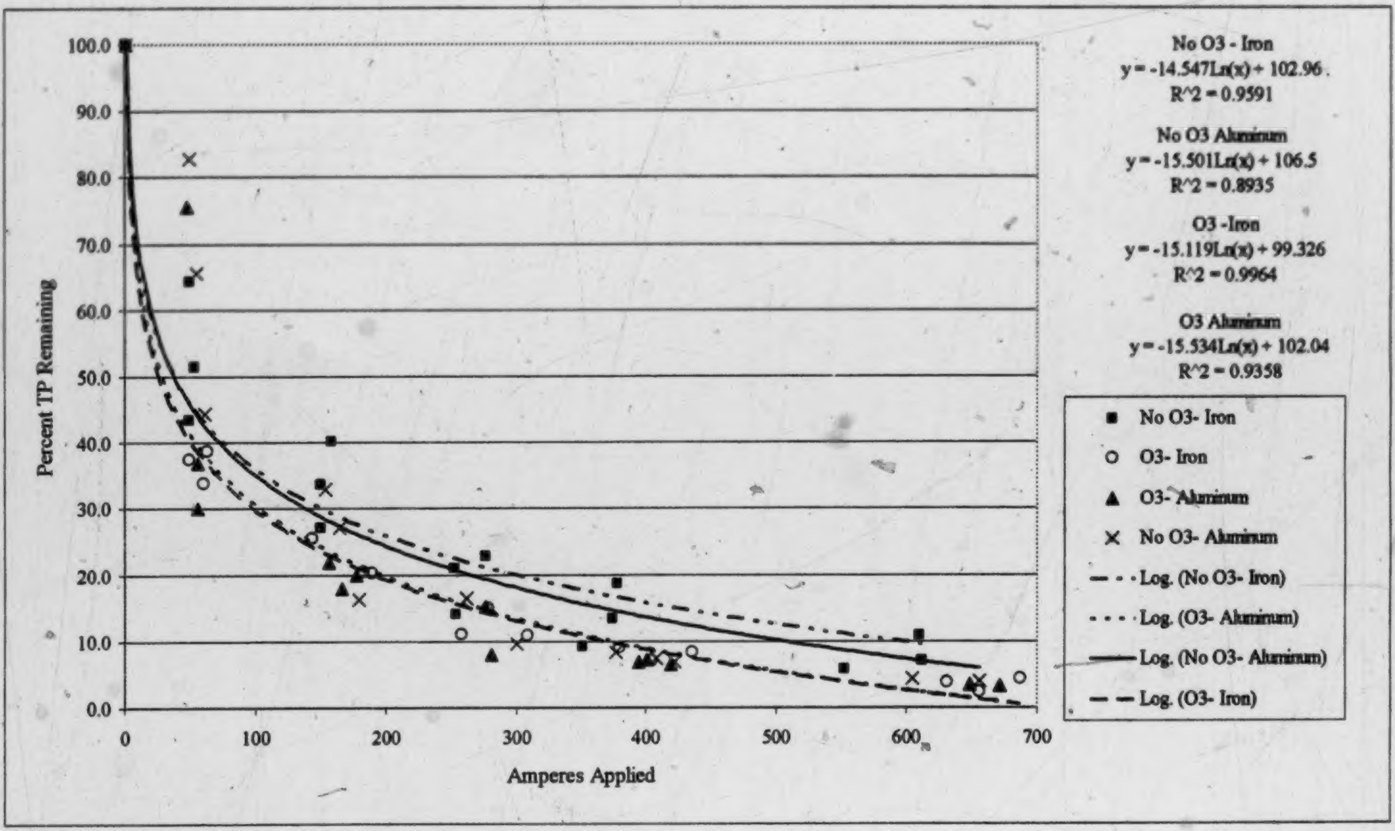

Figure 4-8 Phosphorus Remaining Best Fit Equations

ampere applied range. The residuals (see Appendix H for residual plots and regression analysis) for the no ozone trials confers with what was found in the factorial design that at low ampere applied levels the ozone addition was of greatest importance (i.e. non-ozone trials at early amperes applied do not fit with the trend seen). Typically the two sets (ozone and no ozone) lines run statistically parallel (slopes of -14.5 vs -15.2 for iron and -15.5 vs -15.5 for aluminum) as supported by the ANCOVA statistical analysis (for the straight line natural logarithmic graph and ANCOVA analysis see Appendix H and I) with the samples with ozone addition seeing slightly better reductions (about 5 to 7%).

When considering the iron and aluminum with ozone and the iron and aluminum without ozone together the difference is statistically significant as supported by the ANCOVA analysis as it shows that percent reductions show a statistically significant difference between the different lines for percent TP reduction for ozone vs. without ozone with a 0.05 significance level.

When considering the iron with and iron without ozone lines individually there is a statistically significant difference as confirmed by the ANCOVA analysis as it shows that percent reductions show statistically significant difference between the different lines for iron with ozone vs. iron without ozone with a 0.05 significance level. For the aluminum electrode there is a significant difference between the ozone vs. non-ozone lines only if 0.25 significance is used. If 0.05 significance is used there is insufficient evidence for the ozone vs. non-ozone aluminum runs to prove that there is significant difference between the lines meaning that the lines may be different but there is not enough information to confirm this. For discussion on the use of ANCOVA and the ANCOVA spreadsheets see Appendix I.

These results generally concur with the factorial design as the main effect of ozone was to see create 9.8% improvement in performance however this included the vast improvement seen at the lower ampere applied levels with the ozone added at an equal statistical balance with the seven pass removal so when considering the diminishing returns the 5 to 7% performance improvement seemed appropriate.

4.3.3.4 COD

The COD percent reductions were overall not as effective as the phosphorus removals (50 to 60% reductions for COD and 90 to 100% for TP at higher amperes applied) but the trend in reductions also followed a natural logarithm transformation to yield a linear relationship. The straight line plot, residual plots and regression analysis can be found in Appendix H. Figure 4-9 illustrates the best fit curves.

From this it is seen that for the ozone and non-ozone runs for virtually no difference in the curve was seen. All these values show good R square values meaning the variation of the data was well explained by the regression equation. The lines are significant and the residuals plots show adequacy of fit for all curves. The results of the regression analysis and residual plots can be found in Appendix H. With iron virtually identical results were found in terms of the best-fit equation for both ozonated and non-ozonated samples and the ANCOVA analysis finds no significant difference between the two. For aluminum there appears to be a small improvement when ozone was used over when it is not used. An ANCOVA analysis

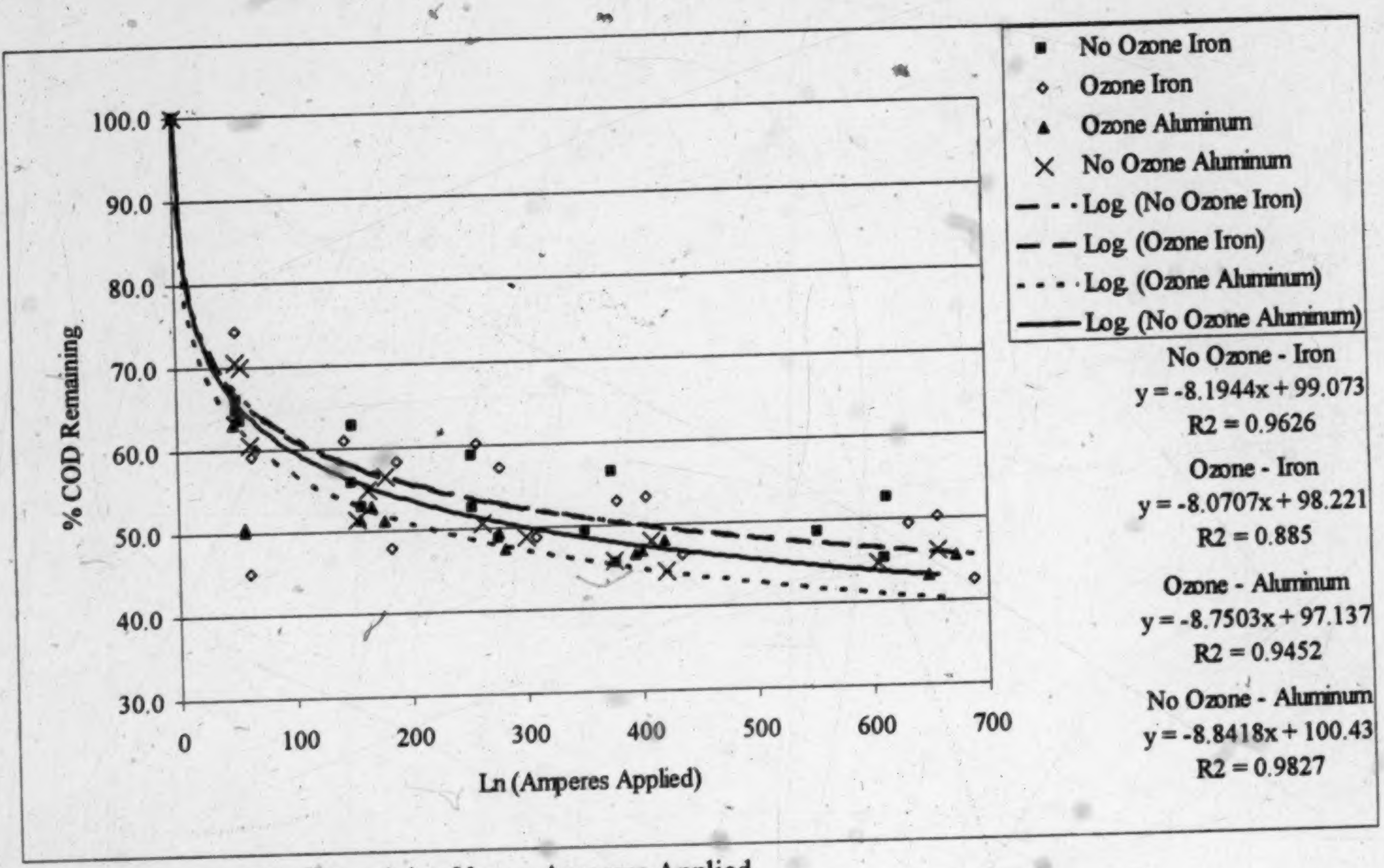

Figure 4-9 Percent COD Remaining Verses Amperes Applied

was performed which showed that this difference was significant at the 0.05 significance level. Therefore, it is determined that the ozone dose when using the aluminum does make a significant difference at the 0.05 level over the ranges tested. The advantages of aluminum with ozone over the iron was even more pronounced as there appears to be typically about a 6 to 8% improvement depending on the amperes applied.

An ANCOVA analysis confirms this suspension as the difference between the aluminum with ozone vs. the iron with ozone is significant at the 0.10 significance level. This large performance improvement is in contrast to the factorial design results as it suggested that the ozone was the more important main effect in comparison to the electrode selection. This analysis shows that at the higher amperes applied where the model used fits the wastewater stream very good the results show that aluminum electrode was without a doubt the superior electrode and it looks more important than the ozone addition. Although what was not apparent by this charting and regression analysis was the impact of the ozone dose near to the beginning of the run (low amperes applied) where it was expected based on the factorial design to have its best performance impacts in comparison to higher amperes applied. Further research is required to determined in what type of scheme and what kind of doses the ozone addition should encompass. The ozone did have some effect on performance but establishing enough confidence to produce a cost benefit effect of ozone at different amperes and treatment schemes could benefit from future analysis.

4.3.4 Water Quality Parameter Assessment

As the above analysis has shown that the aluminum electrode with ozone generally produced the best removals over the parameters tested all further testing was conducted with these settings and the parameters measured were expanded to include the various nitrogen forms, metals analysis, temperature change, BOD and fecal coliforms, (*Bacillus subtilis* and *Cryptosporidium spp.* were also tested but only fecal coliforms were tested at the same time as all the other parameters.) This was to give a better confidence in the systems ability to treat different water quality parameters in addition to further confirming it performance with respect to pH, COD, TSS, and TP. As such this discussion will focus primarily on the results from the eight additional test runs using the aluminum electrode with ozone and also the runs completed under these condition which were included as part of the previous analysis.

The salt addition for these tests varied slightly as they were conducted with 2.6 mg/L additions and 3.4 mg/L for 0717R1, 0717R2, 0719R1 and 0719R2. The goal of the salt addition was to ensure that the unit would operate consistently at the maximum amperes applied. The use of higher salts beyond what the test unit's maximum amperes allowed did not impact the results significantly as discussed in section 2.4.3. The higher salt additions were used towards the end of the testing as the machine seemed to be declining in ampere output so the addition salts were used to ensure more consistent amperes applied for all testing. The impact of the different salt additions on the operational costs of the system will be discussed in a later section. As such the runs which used the aluminum electrode with ozone addition and had a 2.6 to 3.4 mg/L salt increase include 0510R1, 0523R2, 0709R2, 0711R1, 0711R2, 0713R1, 0713R2, 0717R1, 0717R2, 0719R1 and 0719R2. These runs are the focus of this discussion and provide the majority of the data for the figures included in this section.

In certain cases the new water quality parameters had also seen limited measurements under different conditions (i.e. aluminum without ozone). When appropriate these results will also be included as part of this discussion although defining there performance under different conditions was not the primary purpose here.

4.3.4.1 Temperature

Typically temperature was an important parameter in conventional wastewater treatment. Here the temperature results and considerations for the project data analysis will be discussed.

The temperature change from the process was not recorded accurately on all runs due to tight time constraints on the measurement. However on selected runs this parameter was tested to give an idea of the expected temperature change as temperature of the water itself is an important ecological consideration as seen in Table 2-3.

Section 2.4.5 highlighted the optimal change in temperature the test water will experience when exposed to an electrical current. Using the formula presented there the expected optimal change under ideal conditions was compared to the actual change observed during test runs when both the initial and final temperature were measured. Table 4-10 shows these results. All tests listed were aluminum electrode with ozone except for 0523R1 and 0709R1 which were run without ozone.

Table 4-10 Temperature Change from Before to After Treatment

Run Code	Applied Amps	Temperature Increase	Predicted Increase	Difference
0510R1	671	7.6	7.5	-0.1
0523R1	604	8.5	6.7	-1.8
0709R1	422	3.7	4.7	1.0
0709R2	394	2.6	4.4	1.8
0711R2	571	7.1	6.4	-0.7
0713R1	349	5.3	3.9	-1.4
0713R2	592	4.7	6.6	1.9
0717R1	403	6.0	4.5	-1.5
0717R2	666	5.9	7.4	1.5
0719R1	333	4.9	3.7	-1.2
0719R2	618	7.4	6.9	-0.5
			Average	-0.1
			Median	-0.5
			Confidence Level(95.0%)	0.9

From Table 4-10 it is seen that the actual increase and the predicted increase were close with the predicted error between the two averaging 0.1 °C lower than the actual increase. The 95% confidence level for this error data set was quite high however at 0.9 (i.e. the error between the predicted and actual temperature change expected by the process is -1.0 to 0.8 °C). Therefore, when considering thermal impacts of the process and predicting temperature changes by the process, the theoretical equation is acceptable to use a guide. Local considerations of the receiving water must be used in determining the thermal ecological considerations from the wastewater temperature increase due to the electrofloc process.

It is important to remember that the theoretical temperature change is based only on the electricity added under ideal conditions. In reality other factors such as insulation factor of the holding and process tanks and the temperature of the venturi injected ozone/air would impact the temperature change.

4.3.4.2 pH

The pH of the wastewater typically increased as more amperes were applied. Figure 4-10 shows all the pH data taken from single pass experiments. From the figure it is clear that a general trend exists between pH and the amperes applied. As the amperes applied increased the average pH increased. The average pH of the collected wastewater was pH 7.28 ranging between of pH 7.70 and 6.83 with the vast majority of the data being between pH 7.2 and 7.5.

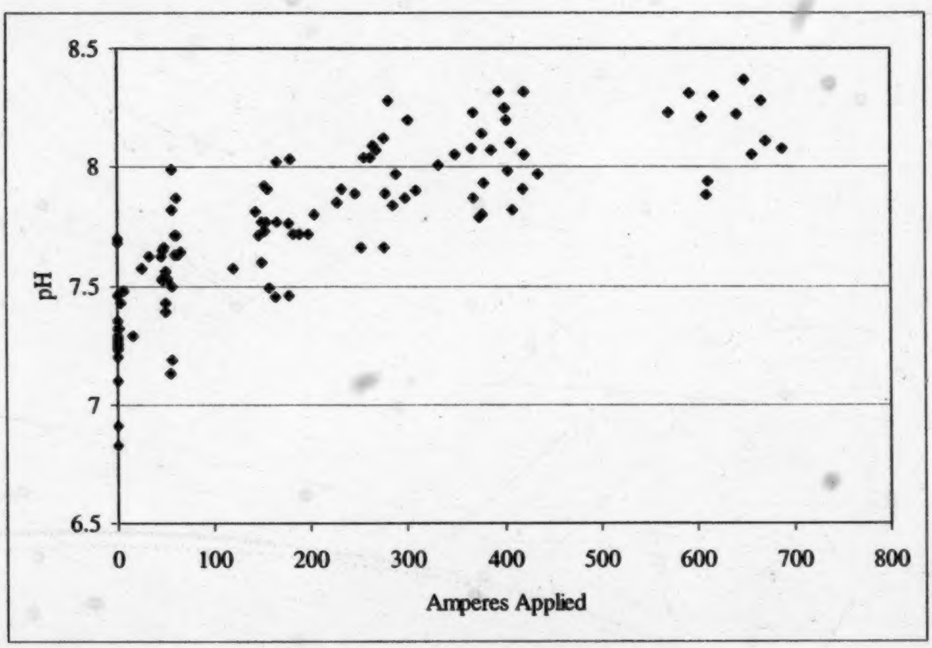

Figure 4-10 pH verses Amperes Applied All Single Pass Data

For the 26 samples with over 400 A applied the average pH was 8.10 with a range between pH 7.82 and 8.37. Figure 4-11 shows the specific curves for the phase 2 samples conducted with ozone addition and the aluminum electrode.

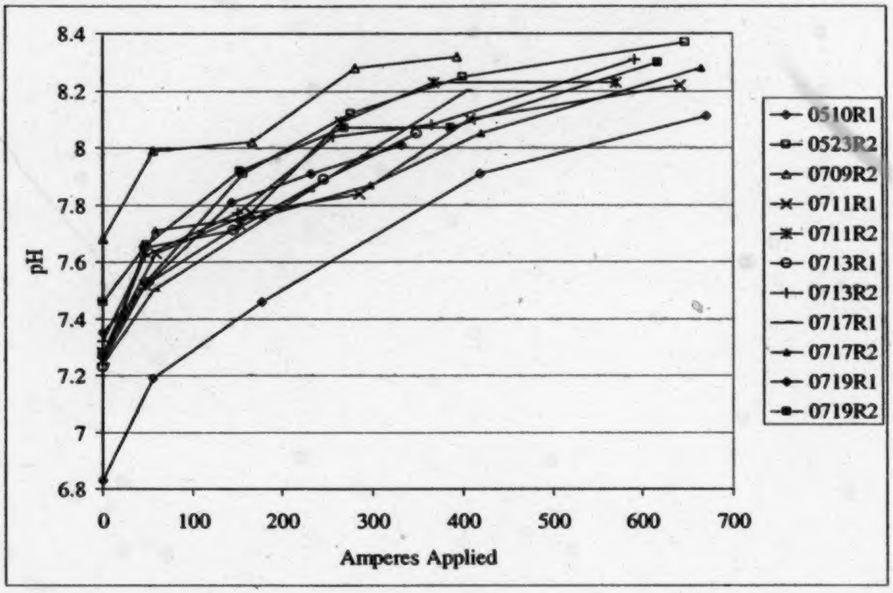

Figure 4-11 pH change versus Amperes Applied for All Sample with Ozone and Using the Aluminum Electrode

From this figure it can be seen that the relative increase in pH with additional amperes applied is reduced as more amperes were applied. It is believed that this curve will eventually peak off and additional amperes applied will not result in significant pH changes. This level appears to be further out in amperes applied than any results obtained in this study but through extrapolation it would appear to be somewhere between a pH 8.7 and 8.2.

The general cause of the pH increase can be related to the following equation previously presented in section 2.4.1:

$$2H_20 + 2e- = H_{2(g)} + 2OH^- \qquad (2-2)$$

This reaction occurring at the cathode creates the hydrogen gas causing the flotation and causes the pH to increase as the hydroxide-ion concentration in the water increases. This reaction is one of the dominant reactions that occur in the electroflocculation system (Donini et al. 1994, Koren and Syversen, 1995). The following reaction which would also impact pH is theoretically present.

$$2H_2O = O_{2(g)} + 4H^+ + 4e^-$$

This reaction will theoretically occur at the anode but is often minor compared to aforementioned equation as Koren and Syversen (1995) report it typically only occurs at very high current densities. Other literature (i.e. Chen et al., 2000) suggest that the two reactions work to neutralize pH (i.e. the neutralizing reaction dominates during the appropriate acidic or alkaline condition to push pH levels towards a pH 7). The experience of this project shows that equation 2-2 dominates in that the reaction creating the hydrogen ion does not seem to prevent pH increase at least not in the pH ranges (6 to 8) and currents used in this project. The minor reaction may however prevent larger pH increases that may otherwise occur if not for its contribution.

4.3.4.3 Total Suspended Solids Results

Figure 4-12 indicates TSS results when using an aluminum electrode with ozone addition. As was found in the multiple conditions analysis this chart shows that the TSS reduction was somewhat sporadic. This was despite the fact that the same testing conditions were used. The chart also shows that the 45 mg/L B.C. marine discharge limit was met in most cases by about 300 amperes applied point. The exceptions to this were the 0717R1, 0717R2 and the 0523R2 test runs each of which required more amperes to meet that requirement.

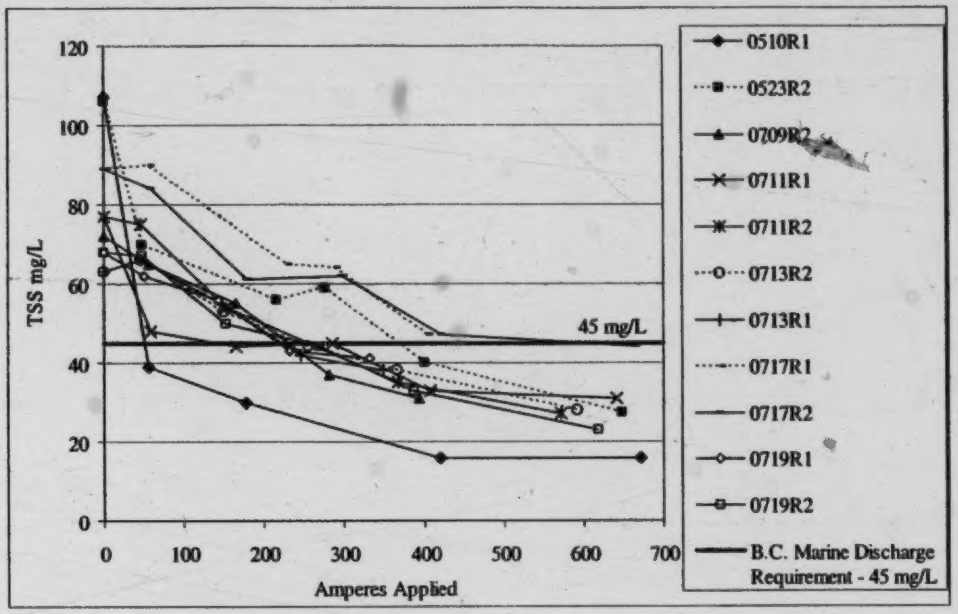

Figure 4-12 TSS Reduction

4.3.4.4 COD and BOD Results

The averaged BOD of collected samples was 160 mg/L with a range of 193 to 145 mg/L. The following graph shows all the valid BOD_5 results collected for the PE and separated sample (these do not include those were the Dissolved Oxygen (DO) uptake was not at least 2 mg/L). The Appendix A lists the results for all the samples.

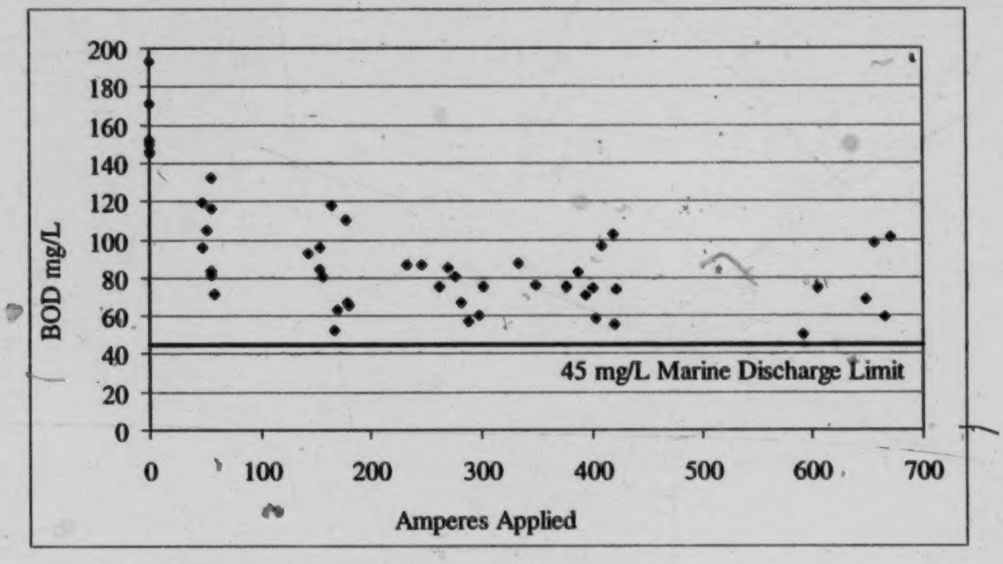

Figure 4-13 BOD$_5$ Results

Figure 4-13 shows the results of the BOD$_5$ experiments. Figure 4-14 shows the performance in COD and BOD for the runs recorded. These results show that the test unit failed to treat sample to levels below 45 mg/L as BOD$_5$ in all cases. These values also show quite a large range in the performance levels achieved. Figure 4-14 shows the BOD$_5$ data as well as the COD results.

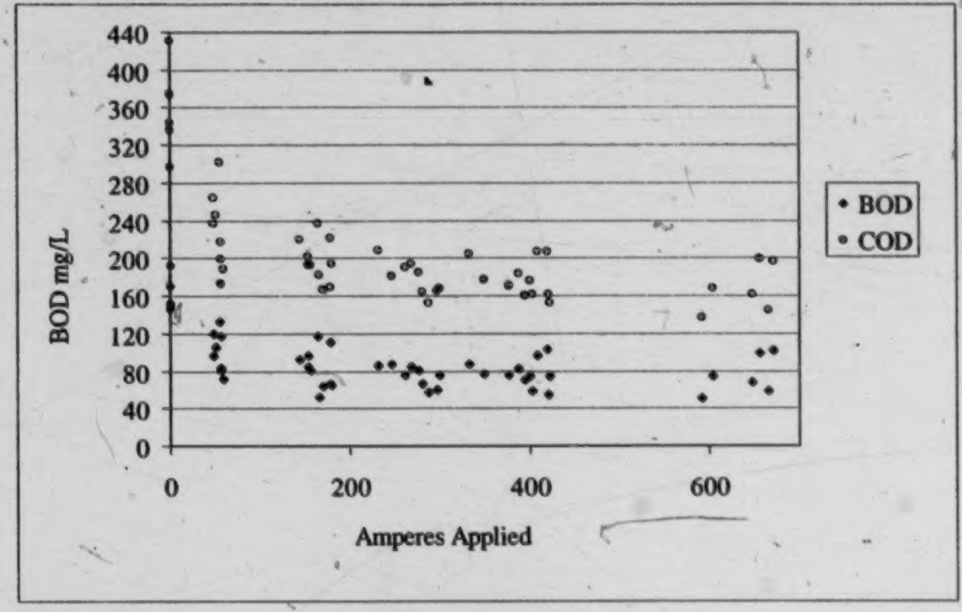

Figure 4-14 BOD_5 and Comparative COD Results

From this graph it is clear that a distinct relationship exists between BOD_5 and COD for this wastewater. Grady et al. (1999) suggest that for domestic wastewater $COD = 2.1(BOD_5)$ while Metcalf and Eddy (1991) suggest that $COD = 2.27(BOD_5)$ be typically used. A review of typical Goldbar WWTP values for found in Table 2-6 suggest that the typical relationship found indicated a value of $COD = 2.19(BOD_5)$. For the course of experiments conducted the primary effluent COD/BOD_5 relationship was found to be 2.26 which is a reasonable expectation. For the Electrofloc^{PLUS} treated effluent the general relationship holds as seen in Figure 4-15. With average relationship for treated and separated samples being 2.35 with low amperes applied being slightly higher than this while at the higher amperes applied the average is a bit lower than this value and is in line with the 2.26 seen for the primary effluent. The group of samples that do not follow the general trend are the blended samples which generally show a much higher ratio meaning that the BOD$_5$ blended samples gain relative to COD blended samples. Table 4-11 summarizes the specific differences in removal percentage between the BOD$_5$ blended samples and the COD blended samples (all samples used ozone and aluminum electrode with ≥ 2.6 g/L salt addition).

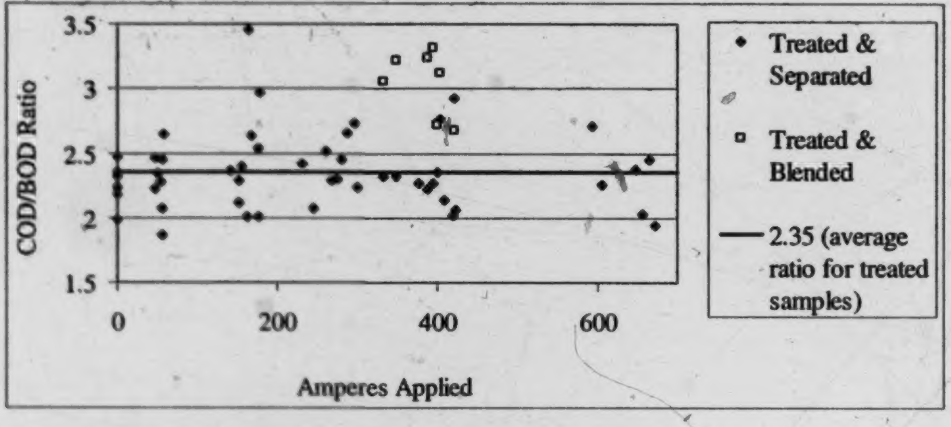

Figure 4-15 COD/BOD$_5$ Ratio

Table 4-11 Blended vs. Separated Reductions

		Percent Reduction					
	Amperes applied	Separated			Blended		
Test Code		COD	BOD	Difference	COD	BOD	Difference
0523R2-7	400	53	51	2	17	25	-8
0709R2-7	394	53	52	2	17	41	-24
0713R1-7	349	48	48	1	8	33	-25
0717R1-7	403	46	61	-15	9	42	-33
0717R2-7	421	46	63	-18	15	37	-22
0719R1-7	333	45	49	-3	19	42	-23
0719R2-7	387	51	52	-1	5	36	-31
Averages	384	49	54	-5	13	37	-24
Std. Dev.	31.5	3.6	6.0	8.3	5.3	6.3	8.2

A simple t-test (using the Microsoft Excel, t-Test: Paired Two Sample for Means built in data analysis) was performed to see if the differences were significant.

In the case of the separated samples the differences were not statistically significant (0.05 siginificance level) that is to suggest there is insufficient evidence to suggest a difference in percent removals between the COD and BOD while in the case of the blended sample the differences were found to be significant and therefore suggesting that Electrofloc^{PLUS} process was causing the reduction of BOD$_5$ in the blended sample at rate greater than was seen in the COD. Figure 4-15 shows the relationship between COD/BOD ratio and that a consistent relationship exists over the course of all non-blended samples. Therefore, in terms of the test unit's performance on the Goldbar wastewater, BOD$_5$ of a treated sample can be estimated as COD/2.35. Figure 4-16 shows the curves for the reductions of COD for all samples tested for COD and which were treated with the aluminum electrode with ozone addition and a salt addition of ≥ 2.6 g/L salt addition.

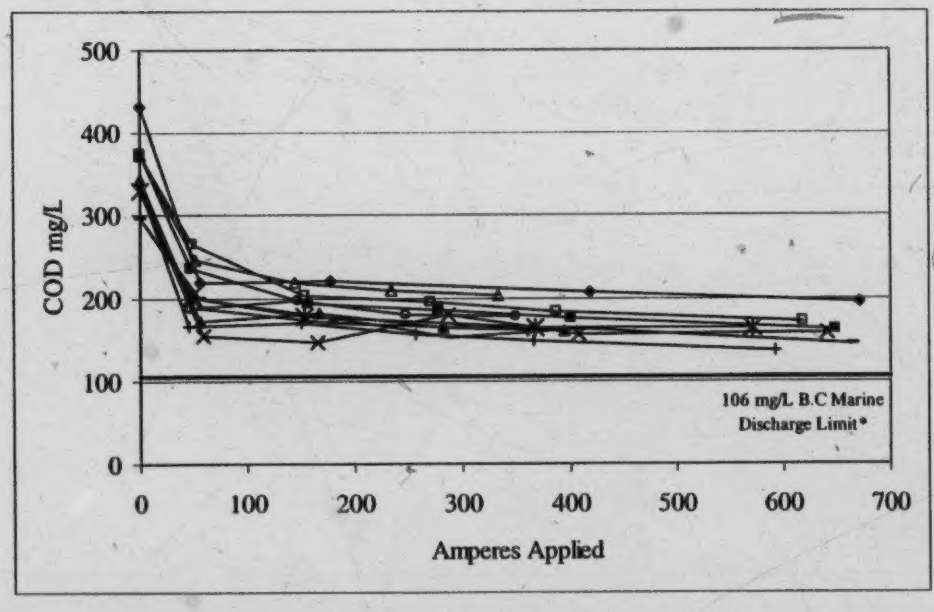

Figure 4-16 COD Reduction Curves (*note the 106 mg/L guideline is based on treated separated sample having a BOD$_5$ = 2.35(COD))

Figure 4-16 shows that the reductions were insufficient to meet the desired objectives for all wastewater samples tested. The low overall reduction was a bit of a surprise. However, it was thought that about 35% of the COD in the PE was soluble (typical value for Gold Bar wastewater – see table 2.6) and is not easily removed by the test unit as electroflocculation does not easily remove soluble organic compounds (Rock, 1996). This makes the reductions found of around 50 to 60% appear to be approaching the limit of the units capabilities for COD removal at least with the application of a reasonable amounts of applied amperes. Poor COD removals are not abnormal in electroflocculation as Joffe and Knieper (2000) reported COD removals of only 20.6% and BOD removals of only 32.4% with the test unit and water sample used finding good TSS removals (84.2%). Pouet and Grasmick (1995) saw a 30% removal of the soluble COD with a municipal wastewater treated with electrocoagulation and electroflotation process. A maximum total removal of 75% COD was obtained in there study. Mills (2000) reports COD reductions from 280 mg/L to below detection limit in treating landfill leachate and COD reductions from 484 mg/L to below detection limit and claims potable quality effluents from the treated effluents. These results were difficult to accept based on other literature and the results here.

4.3.4.5 Total Phosphorus Results

The test unit showed very good removals of total phosphorus. Figure 4-17 shows that exceptional overall consistency of performance was found. With the exception of one run (0523R2) all samples were below the 1 mg/L discharge limit by

160 amperes applied.

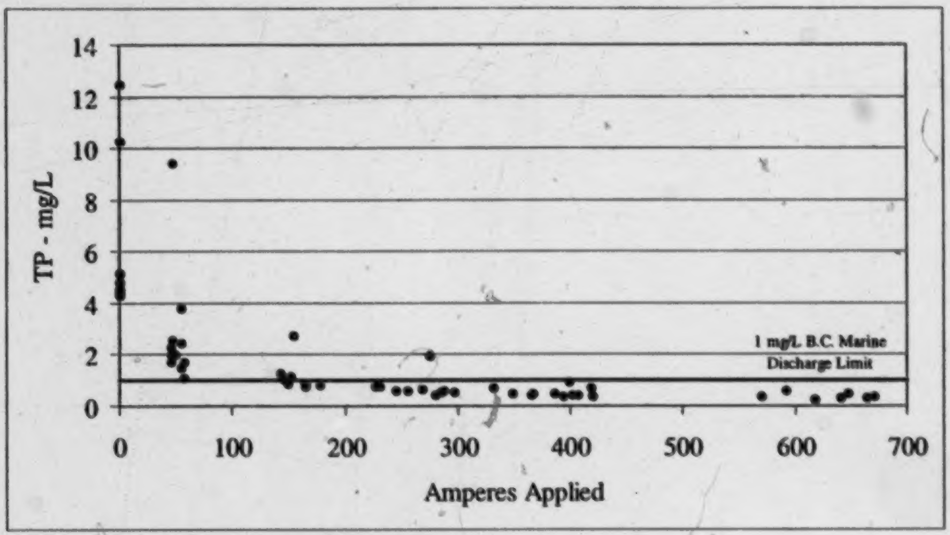

Figure 4-17 Reduction of Total Phosphorus

These results seem to be in line with what much of literature suggests for electrofloculation processes. Eilbeck and Mattock (1987) suggested that sacrificial dissolution of metal anodes particularly aluminum to be an extremely efficient in removing phosphates in comparison to chemical precipitation.

4.3.4.6 Ammonia and TKN Results

Figure 4-18 shows the performance for ammonia in terms of actual reductions in a comparison between ozonated and non-ozonated paired runs with the aluminum electrode. The comparison was preformed with three different wastewaters.

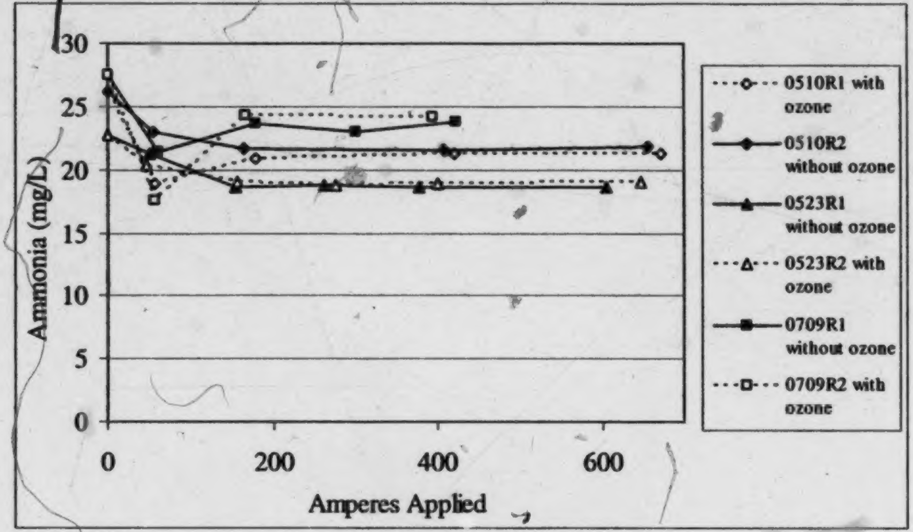

Figure 4-18 Ammonia with Added Ozone and Without Ozone (Aluminum Electrode)

These results indicate that there was no significant difference in removals between the between the ozonated and the non-ozonated samples. Figure 4-19 shows the performance for ammonia for all the tests runs using the aluminum electrode with ozone addition.

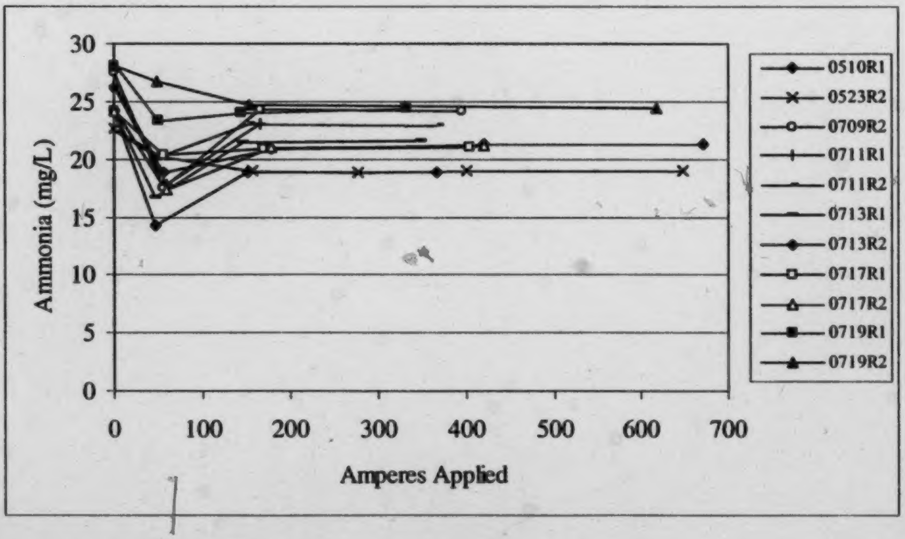

Figure 4-19 Ammonia Reduction Performance

Figure 4-19 shows that very little reduction was seen for the ammonia. The interesting note here is that there was an initial decline that was relatively high but then the concentration "rebounds" back-up towards there initial values. In the end removals of only 3 to 5 mg/L were found while the initial removals are almost double the final removal. The analytical order of processing through the distillation unit for ammonia measurement did not cause this phenomenon as full randomization was used to determine the order in which the samples were tested.

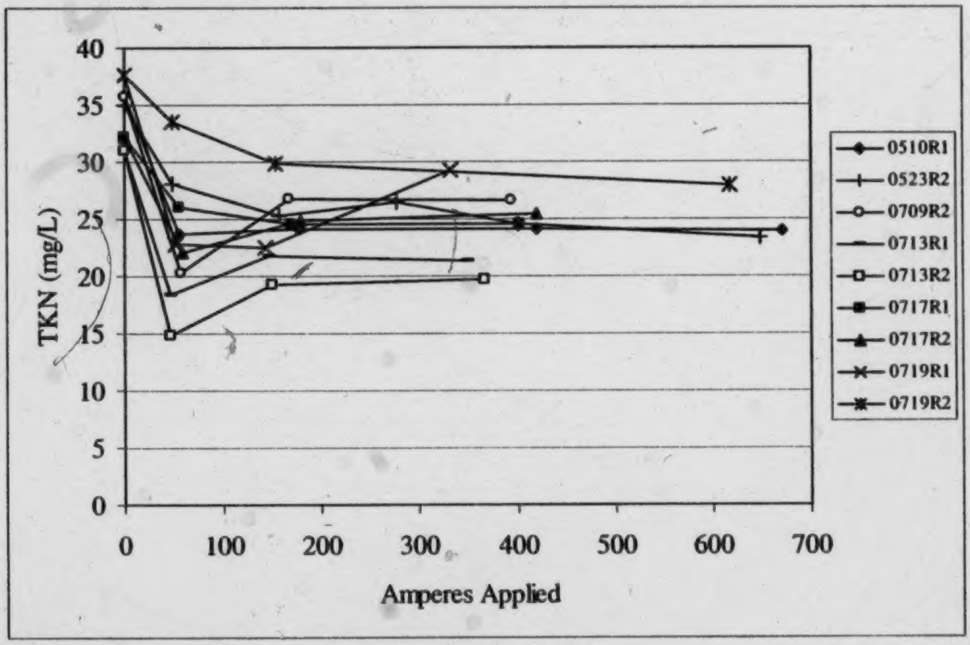

Figure 4-20 TKN Reduction Performance

Some of the results here show good early removals with a "rebound" effect occurring afterwards. After the "rebound" the TKN values tend to stay at the same level. The main difference was that the initial removal was greater for TKN than for ammonia as was the overall removal. It appears that all the organic nitrogen component of the TKN was removed but the ammonia nitrogen remains and causes the TKN curves to follow the same rebound pattern as the ammonia samples, just not as pronounced. Figure 4-21 shows the comparative results between the ammonia and TKN results.

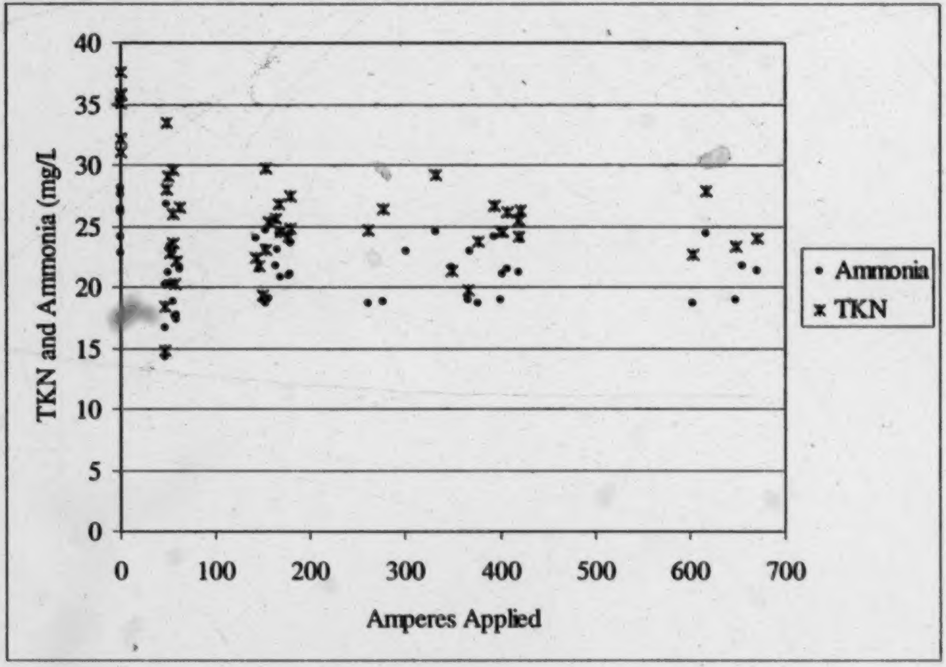

Figure 4-21 TKN and Ammonia Comparison

As can be seen by Figure 4-21 the TKN results were generally very similar in absolute values to the ammonia values. So it was concluded that in fact little ammonia is removed by this process while organic nitrogen was being removed.

As a final note four runs were successfully tested for nitrogen forms using the iron electrode with ozone on 0426R1, 0426R2, 0220R1 and 0222R1. These results are not on the graph but can be found in Appendix A. The results preformed similarly to what was found with the aluminum electrode with the exception being that the "rebound" effect was not as pronounced but present.

4.3.4.7 Nitrite and Nitrate Results

Figure 4-22 shows the results of the Nitrite + Nitrate testing. Little can be determined from these samples except that it appeared some removal was possible when the values were high. It is important to note that the 0713R1 and 0713R2 were both very near to the 0.05 mg/L detection limit of the test.

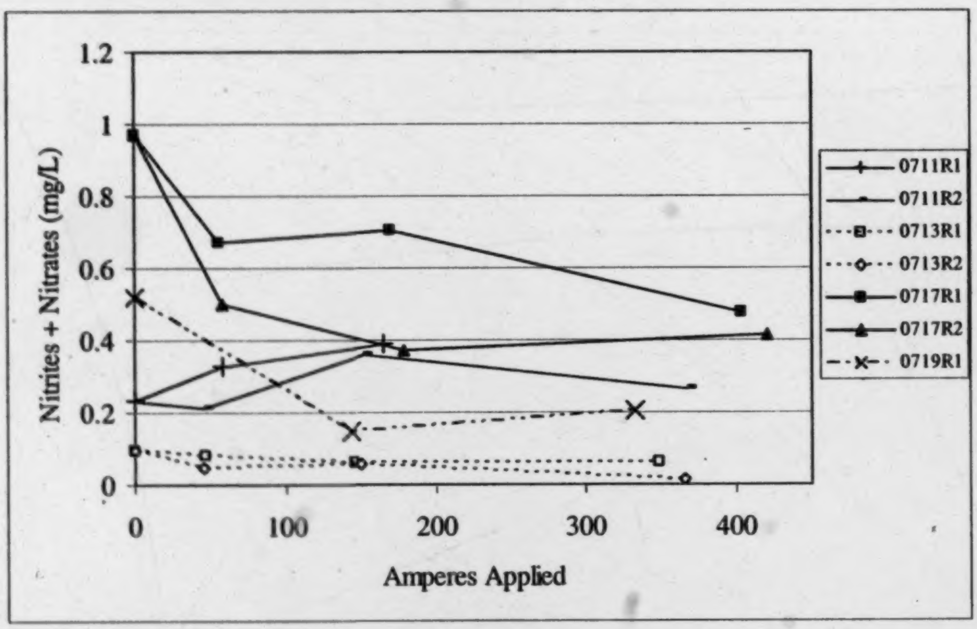

Figure 4-22 Results of the Nitrite + Nitrate Testing

4.3.4.8 Metals Results

The discussion and results for metal analysis were divided into sections including one for the aluminum results and additional sections for the remainder of metals tested including Ag, As, B, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Se, Tl and Zn. The testing involved the use of different primary sample taken from three separate days. All samples were passed through the test unit seven times with ozone addition all three days using the aluminum electrode. The complete raw data set as released by the Goldbar labs can be found in the Appendix E.

4.3.4.9 Aluminum

Some interesting results were found for the aluminum samples. The results can be seen in Figure 4-23. Note that the scale is logarithmic.

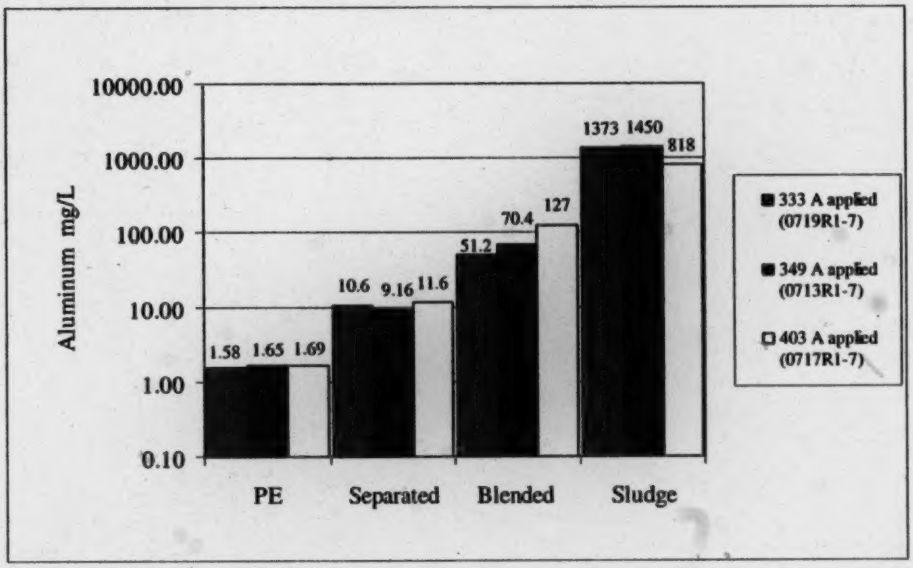

Figure 4-23 Aluminum Results

These results clearly show an addition of aluminum in all streams. The blended sample shows increases in aluminum concentration from 32.4 to 75.1 times the initial concentration in the raw PE with the largest increase correlating with the test run which applied the most amperes (403 A) over the course of the seven passes as would be expected. The separated sample was also elevated in terms of its aluminum content as the concentration was increased by an average of 6.4 times. These data were significant in two respects. First, the aluminum addition was important in terms of the process cost (i.e. since aluminum is clearly a consumable adding up to 125 mg/L aluminum to the sample any operational costs would need to factor in the cost of this). Second, the fact that aluminum was present in the separated stream in significantly higher concentrations than that of the raw PE creates the environmental issue of additional aluminum loads to the receiving environment. Also, the relatively high aluminum levels in the sludge (up to 879 times as concentrated) also create important considerations in the disposal opportunities for the sludge. Aluminum's toxicity is low (Gray, 1999) relative to other heavy metals but the relatively high concentrations makes caution appropriate. Doe (1990) suggested little is known about alum sludge disposal from conventional drinking water treatment in regards to its toxicological impacts on the receiving environment. Information about the toxicological impacts of the of aluminum content in electrofloc treated municipal wastewater sludge would require investigation should the technology develop to a point were significant quantities of this sludge waste was being generated.

4.3.4.10 Non-Aluminum Metals in Blended Sample

From the metals analysis of the blended samples it can be seen that certain metals had significant increases in their concentration which appear not to be explained alone by random sampling discrepancies.

Figures 4-26 and 4-27 shows the concentration in the primary effluent before treatment and the concentration of blended sample. This gives an indication of what metals were added to the wastewater from the process. It is presumed that these metals were added from the electrochemical cell and that the electrode was not a pure aluminum alloy allowing the introduction of other species to the wastewater.

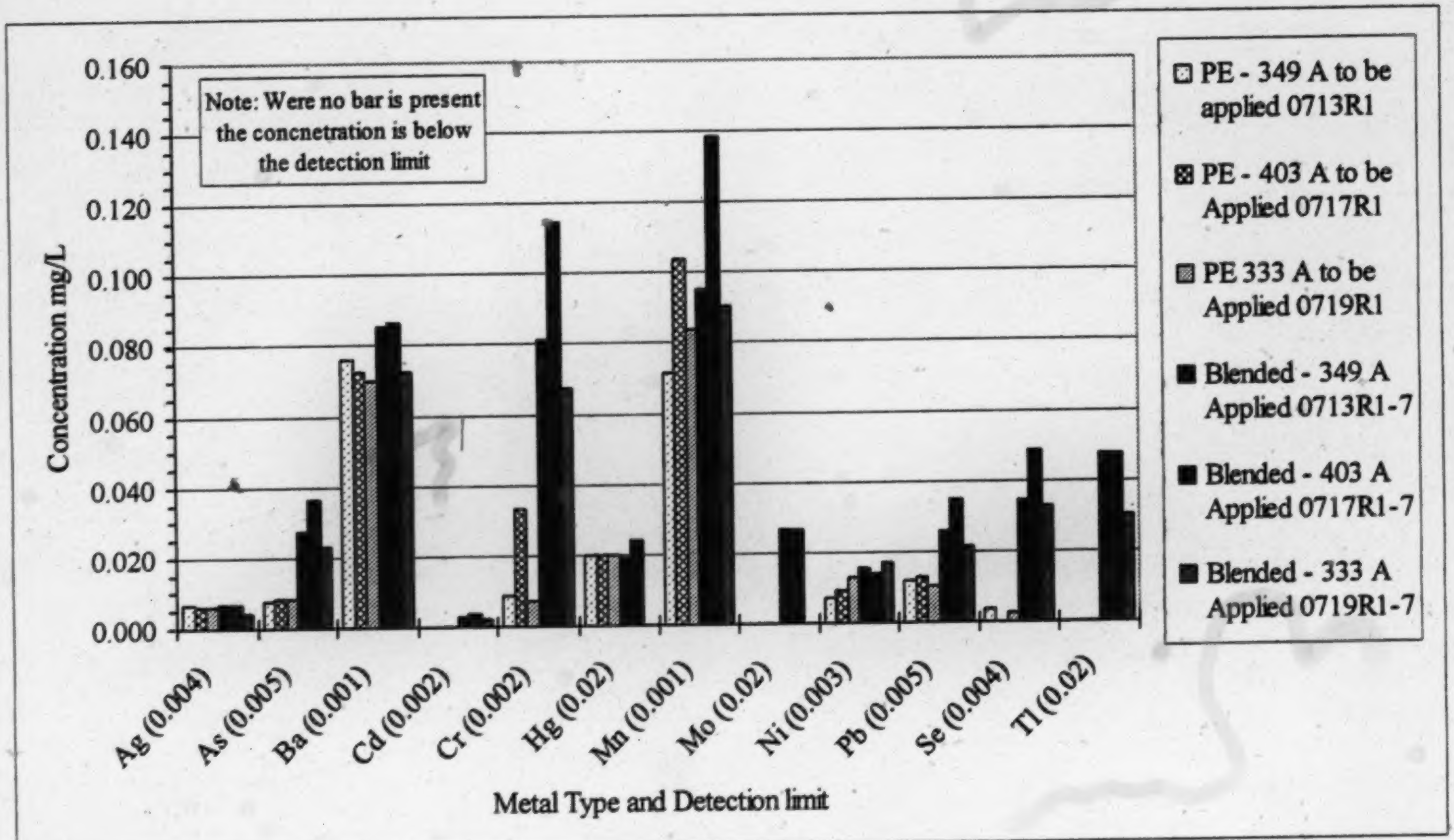

Figure 4-24 Primary Effluent vs. Electrofloc Blended (Ag, As, Ba, Cd, Cr, Hg, Mn, Ni, Pb, Se and Tl)

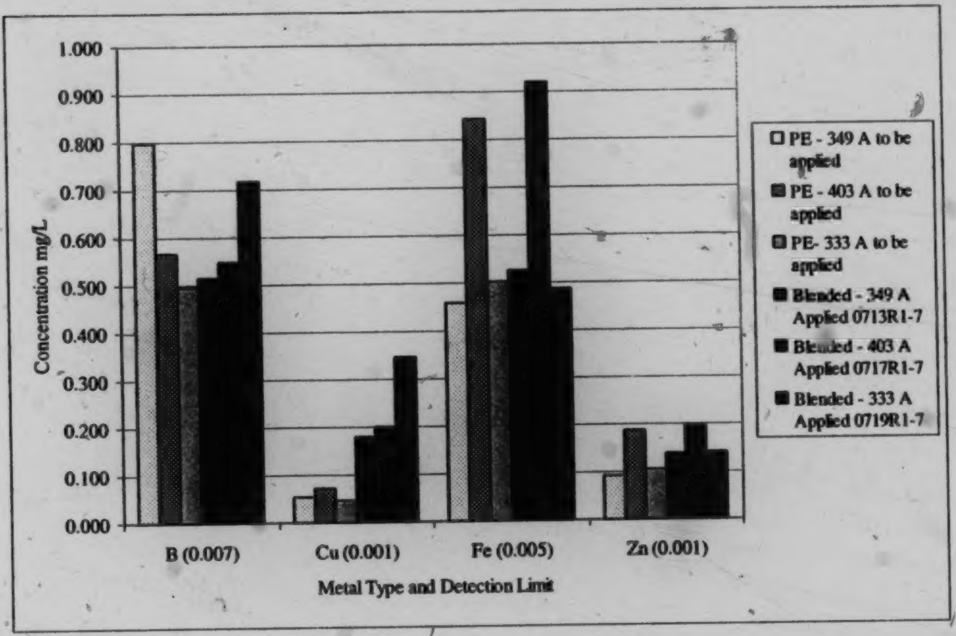

Figure 4-25 Primary Effluent vs. Electrofloc Blended Samples (B, Cu, Fe and Zn)

Possibly the connections to the electrochemical cells were allowing the introduction of the metals present there which would likely include the copper.

4.3.4.11 Metal Concentrations in Sludge

Figure 4-26 on the following page shows the metals in the sludge stream. What is interesting to note here is that all metal species tested increased in concentration in the sludge stream. The iron (Fe) increased to very high levels despite the fact that no Fe change was seen in the blended sample. This indicates that the electrofloc process is in fact bringing the iron out of the solution and into the sludge. This was seen for all metals as they all had substantially higher concentrations in the sludge than in any other stream. Boron increased the lowest amount, 114%, 146% and 231% of the original primary effluent values for all three runs. Even those metals which are below the detection limit for the primary effluent and separated treated samples (Cd, Hg, Mo and Tl) are well above the detection limits in the sludge suggesting that they were present in the sample in low quantities and concentrated into the sludge leaving the separated treated sample cleaner than it was initially.

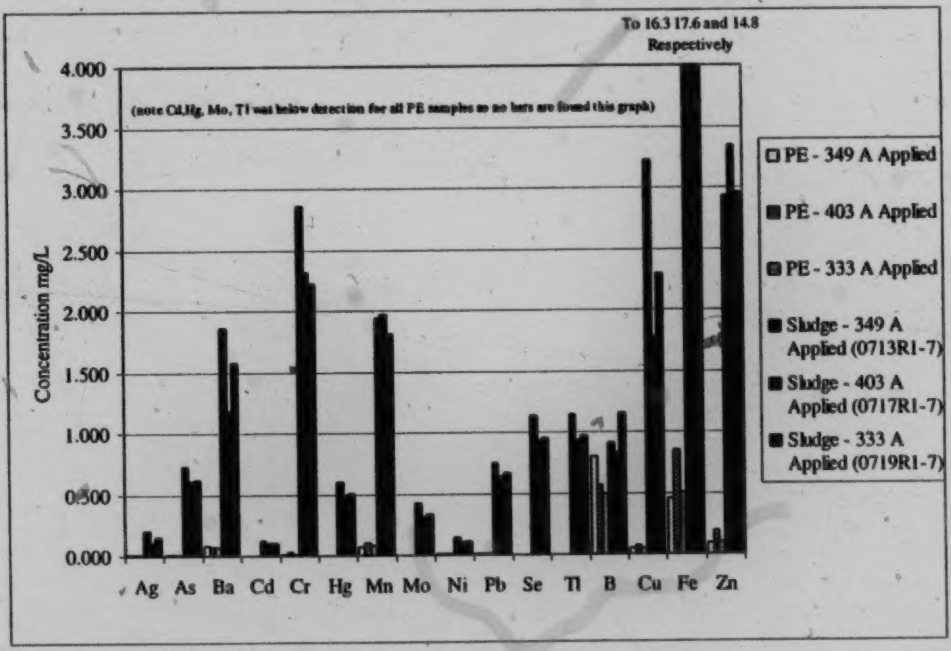

Figure 4-26 Metals Concentration - Primary Effluent verses Sludge

4.3.4.12 Metals Concentration in Separated Sample

The concentration of metals in the separated sample was not considerably reduced from initial values for most metals in most cases. The iron (Fe) does show good removals as 75% (with 349 A), 87% (with 403 A), and 76% (with 333 A) were removed. Figure 4-27 shows that consistent removals for other metals were not great overall. It is important to remember that for the As, Cr, Cu, B, Zn and Mn that metal was added to the water from the process (the blended samples had greater concentrations than the PE samples as seen in Figure 4-24 and Figure 4-25) so the fact that the final treated sample has less or equal to what is in the blended sample shows that metals introduced are being captured by the flocs and sent into the sludge. Thus, the final effluent to be released to the environment does not have elevated levels. For Cd, Hg, Mo and Tl the majority of samples from both the PE and the separated streams were below the detection so these are not included in Figure 4-27.

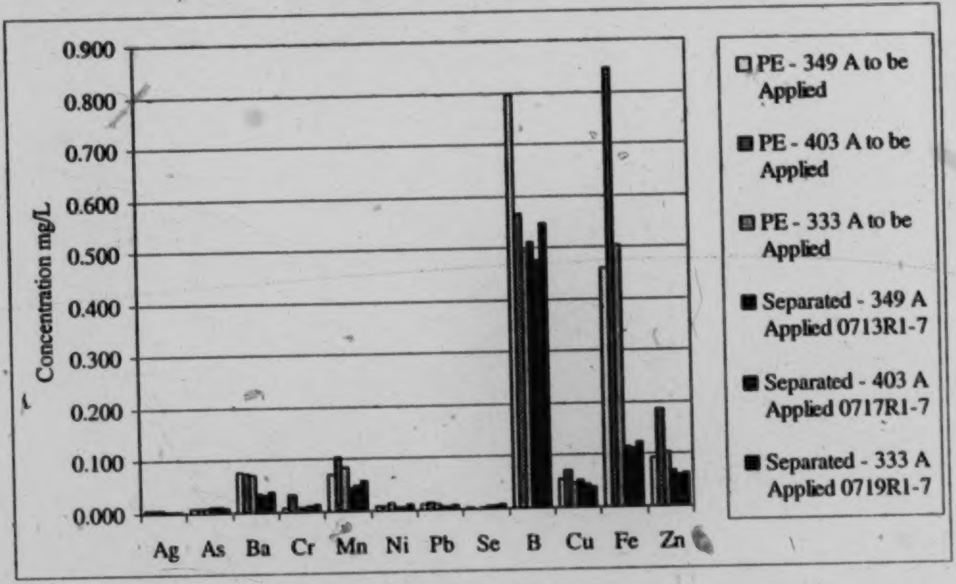

Figure 4-27 Metals in Primary Effluent verses Treated and Separated Sample

4.3.4.13 General Metals Discussion

The metals analysis determined some important points but also left a number in question that will require further research. These questions include: Why does the process add metals other than aluminum and is this dependent on the source of the aluminum (is the aluminum electrode pure or does it contain small amounts of other metals)? Why is the process not more effective in separating the metals from the treated wastewater as many vendors of similar technology claim?

Additionally the data set used for this analysis is somewhat limited. Further research is needed to define the addition of iron when using iron electrodes and also further research is needed to better define the aluminum additions to each stream and the removal performance for other metals.

4.4 Microbiological Assessment

4.4.1 Fecal Coliform Results

The results from the successful fecal coliform tests are found in the following figures. Figure Figure 4-28 shows the test unit performance from six test runs with three different wastewater samples. All tests were run with the aluminum electrode and ozone addition. Also the July 11 wastewater had a salt addtition of 2.6 g/L while the other two wastewaters had a salt addition of 3.4 g/L. The fecal coliform data can be found in Appendix B.

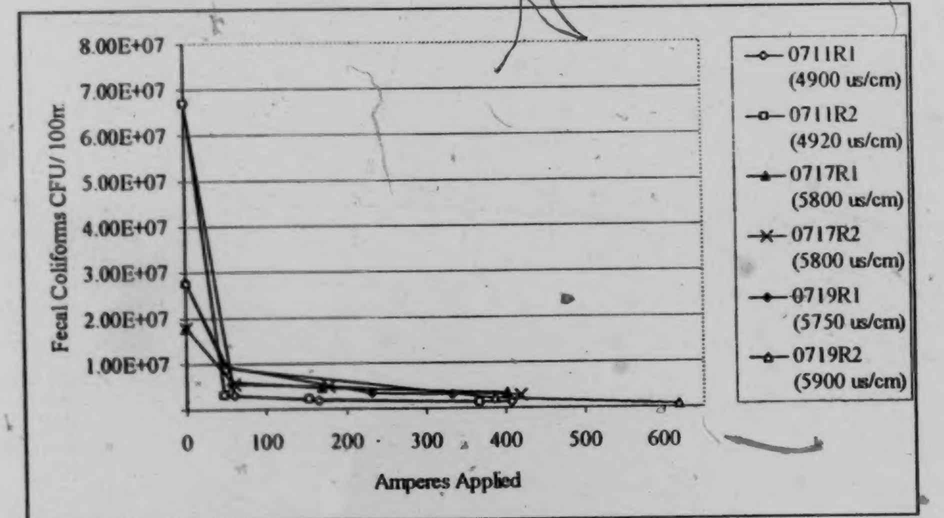

Figure 4-28 Fecal Coliform Reduction Performance

These results show a large variability in the reduction of fecal coliforms. It is believed that the relatively poor performance of sample 0717R1 and R2 relative to the other samples was due to the initial PE not yielding a plate count within the appropriate range of 20 to 60 coliforms and therefore the initial values seen on Figure

4-28 are questionable. Figure 4-29 shows the remaining fecal coliforms in the blended sample and the 95% confidence limits calculated. These results present survival observed.

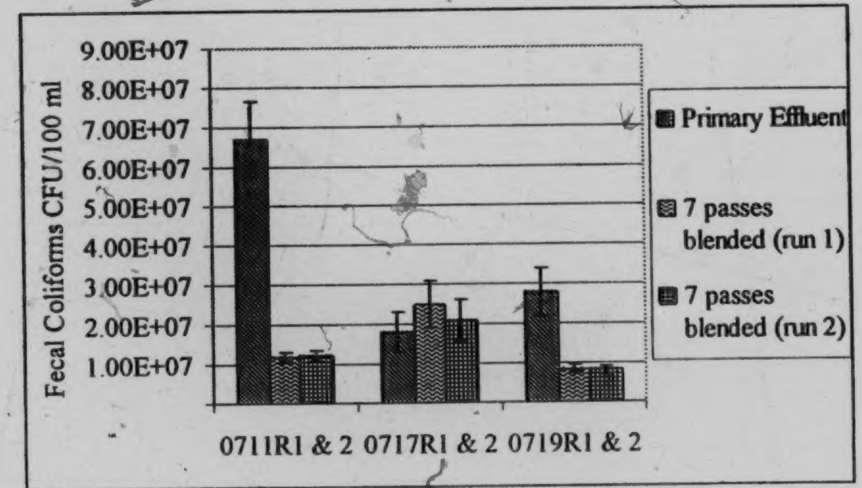

Figure 4-29 Fecal Coliform Blended Sample Performance

These results again are variable (from no reduction for the 0717R1& 2 samples to a 0.75 log reduction for the 0711R1 & 2 samples) with both samples from July 17 showing no significant reductions while the other samples obtain much better reductions. Table 4-12 summarizes the fecal coliform findings in terms of the Log reduction found.

Table 4-12 Fecal Coliforms - Log Reductions

	0711R1		0711R2		0717R1		0717R2		0719R1		0719R2		Average	
Sample Description	Amperes Applied	Log Reduction	Amperes Applied	Log Reduction	Amperes Applied	Log Reduction	Amperes Applied	Log Reduction	Amperes Applied	Log Reduction	Amperes Applied	Log Reduction	Amperes Applied	Log Reduction
1 pass	59	1.36	47	1.32	56	0.47	59	0.52	51	0.48	48	0.49	53	0.63
3 passes	165	1.57	153	1.53	169	0.60	179	0.58	232	0.92	n/a	n/a	180	0.86
7 passes	408	1.73	368	1.73	403	0.72	421	0.80	333	0.97	387	1.11	386	1.02
11 passes	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	618	1.61	618	1.61
7 passes (blended)	408	0.75	368	0.75	403	-0.14	421	-0.07	333	0.53	387	0.54	386	0.23

This table shows that at approximately 386 amperes applied a 1.0 log reduction in fecal coliforms was found. The blended sample at the same amperes applied the reduction was only a 0.2 log reduction. When comparing these results with those found in Table 2-2 for the reduction of fecal coliforms using conventional treatment it is found that a 1 log reduction in fecal coliforms is expected (10^7 to 10^6). This system performance is in line with the reductions expected using conventional treatment.

4.4.2 *Bacillus subtilis* Results

Bacillus subtilis results are a relatively good approximation for determining the test units potential for protozoan reductions, particularly *Cryptosporidium spp.*, as studies have shown that *Bacillus subtilis* is a promising indicator of protozoan oocyst inactivation (Facile et al., 2000). Figure 4-30 shows the unit capabilities in terms of *Bacillus subtilis* reduction. These test runs were spiked to allow for more consistent results and clearer picture of the reductions. As at the dilutions used for the wild strains the potential for interferences with other species was possible so this was avoided.

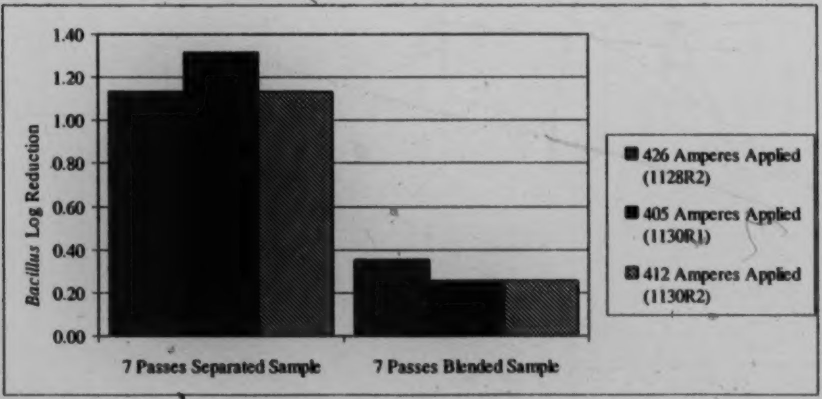

Figure 4-30 *Bacillus subtilis* Reductions

These results show very good reductions in the treated and separated samples while reductions were not as impressive with the blended sample. Table 4-13 summarizes the Log reductions obtained.

Table 4-13 *Bacillus subtilis* Log Reductions

Bacillus subtilis Log Reduction			
Sample	Amperes	Blended	Separated
1128R1 (not spiked)	386	0.18	0.84
1128R2 (spiked)	426	0.35	1.14
1130R1 (spiked)	405	0.26	1.31
1130R2 (spiked)	412	0.25	1.13
Average	407	0.26	1.07

This table shows that the overall average shows a good Log reduction. The samples that were spiked all had slightly better removals than did the non-spiked samples. The first test run (1128R1) was not spiked with lab cultivated *Bacillus subtilis* and only the wild strains were measured.

4.4.3 *Cryptosporidium parvum* Results

Table 4-14 *Cryptosporidium parvum* Infectivity Information

	***C. parvum* Infectivity Information**							***Cyst Batch and Dose Response Information***		
Sample	Oocysts Per Animal	Animals in Cohort	Animals Infected	Proportion Infected	Calculated Log Inactivation	Average Log Inactivation	Average Percent Inactivation	Cyst Batch	b_0	b_1
1206R2-7 (409 A) 13.2 million oocysts/ L	100	5	1	0.2	0.51	0.78	83.32	50	-7.19	3.89
1206R2-7 (409 A) 13.2 million oocysts/ L	1000	5	3	0.6	1.05			50	-7.19	3.89
1206R3-7 (409 A) 13.2 million oocysts/ L	100	5	2	0.4	0.26	0.26	44.53	50	-7.19	3.89
1206R3-7 (409 A) 13.2 million oocysts/ L	1000	5	5	1	<0.8			50	-7.19	3.89
Blank A (spiked Buffer)	50	5	2	0.4	-0.05	0.22	40.37	50	-7.19	3.89
Blank A spiked Buffer)	500	5	4	0.8	0.49			50	-7.19	3.89
Blank B (spiked 1206R1-7 (401 A))	50	5	2	0.4	-0.05	-0.05	-10.95	50	-7.19	3.89
Blank B (spiked 1206R1-7 (401 A))	500	5	5	1	<0.49			50	-7.19	3.89

These data show that the average log inactivation for the trials generally agrees with what was discovered for *Bacillus subtilis* with a combined average log inactivation of 0.52 and a percent inactivation of 64 percent. This is approximately the same as what was found with the blended *Bacillus subtilis* samples. The infectivity information is subject to some error but when taken in consideration with what the fecal coliform data suggested and more importantly the *Bacillus subtilis* information suggests the values are in the appropriate range of the expected kill using aluminum electrodes with ozone addition. The *Cryptosporidium spp.* results also suggest that the method of using the blended sample to determine kill is an appropriate measure due to the rough correlation of the results between the *Cryptosporidium spp.* and the *Bacillus subtilis*.

4.4.4 Microorganism Reduction General Considerations

The ozone addition normally would be very important for microorganism reduction and would effectively kill most pathogens when applied to most natural water but when using primary effluent the immediate oxidant demand of primary effluent was so high that a very high concentration of ozone was required to meet this demand and allow for effective microorganism reduction. The purpose of the ozone however was as coagulant aid and not a chemical for reducing microorganisms so any benefits realized from the ozone addition were a bonus to the system. The electrical current in the wastewater itself plays a key role in the microorganism reduction potential of the unit. The use of electricity for the sterilization of water has been documented by Allen and Soike (1966). Mills (2000) suggests that the presence of an electrical field will aid in the destruction of bacteria and reports coliform reductions from 4.17 log units to 2.42 log units before separation of solids. These results are much higher than those achieved with this study.

4.5 Power Consumption

For all the graphs that are related in terms of amperes applied the equivalent power consumption or the power consumption in watts that would be required to yield these results in real life conditions can be determined. As can be seen in Figure 4-2 the initial conductivity of most samples lies between 837 μS/cm and 1090 μS/cm with the average being 973 μS/cm. The conductivity increase after the salt addition of 2.64 g/L to the Goldbar primary effluent can be defined by the following equation first reported in Figure 4-2:

Y(final conductivity) = 1443.5*X(salt addition in grams/ litre) + 995

The final conductivity would thus equal 4806 μS/cm. In actual situations a range would be found as seen by the residual around the best fit line in Figure 4-2. Using this relationship and the average initial conductivity of 973 μS/cm a conductivity increase factor of 4.94 was yielded when adding 2.64 mg salt /L.

As per the formulas and example discussed in section 2.4.3 the actual power consumed per pass can be calculated by P = U x I where P = power consumption (W), U = Voltage (V) and I = current (A). From Figure 4-5 average ampere applied column it is seen that a typical pass under these conditions yields approximately 55 A. The voltage of the system is 32 V resulting in P = 32 * 55 = 1760 W was used. Using ohms law R = U / I the actual resistance is determined to be 0.58. Using the conductivity increase factor the resistance that would have been without increasing the conductivity would have been 2.86. From these values and using ohms law U = R x I the required increase in voltage necessary to obtain the same amperes that were experience during the runs was calculated to be 157.3 V. To get the same treatment without increasing the conductivity the power consumption would have to increase to $P = 157.3 * 55 = 8\,652$ W. Using the same principles all figures shown with amperes applied (with a 2.64 g/L salt increase) was approximated in terms of cumulative power consumption /L in kWh/m^3. For an example the electrode power requirement to pass 1000 L through the test unit for the typical 2.64 g/L salt addition sample. The test unit flow rate as discussed in section 4.1.1 was 0.68 L/s or one litre every 1.47 seconds.

8 652 W x Time (S) = Joules or Watt-seconds

8 652 W x 1.47 S = 12718 Watt/L

1 kilowatt hour = 3 600 000 Watt

12718 Watt/ L / 3 600 000 Watt = 0.0035 kWh / L

0.0035 kWh/L X 1000 L = 3.5 kWh/m^3

This approximates the amount of energy that would be required for one pass through the test unit for the wastewater if no salt had been added. Figure 4-31 shows the data from Figure 4-15 in terms of kWh/m^3.

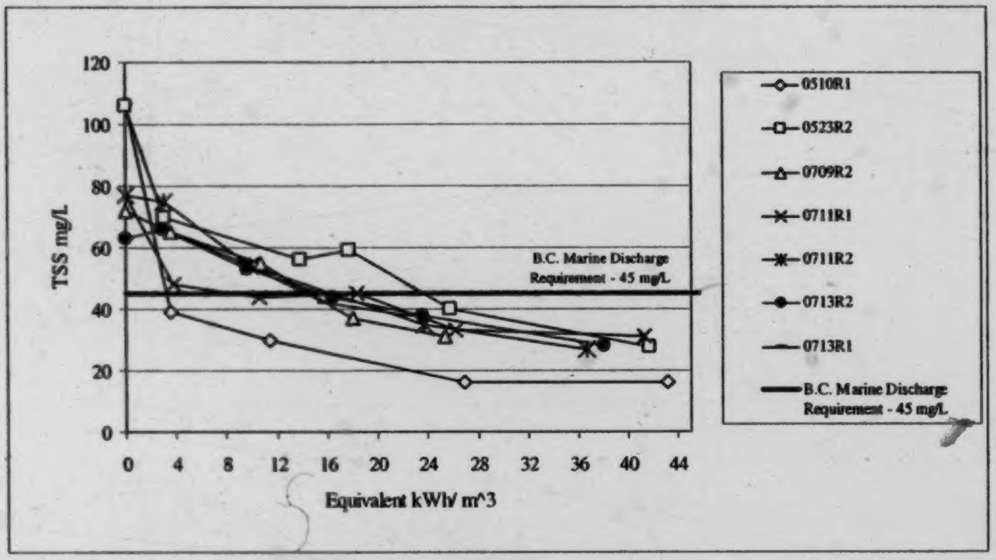

Figure 4-31 TSS in Terms of Equivalent kWh/m^3

These values are heavily based on assumption and can only be used to give a basic idea of the power consumption that would be required to operate the test unit. For all graphs which have samples using 2.64 g/L, Table 4-15 can be used as a conversion between amperes applied and equivalent kWh/m^3.

Table 4-15 Conversion Table for Amperes Applied to kWh/m^3

Amperes Applied (A)	50	100	200	300	400	500	600
Equivalent kWh/ m^3	3.2	6.4	12.8	19.3	25.7	32.1	38.5

These energy consumption rates are extremely high compared to other units listed in the literature. Perhaps this is because the test unit was not really designed for the purpose to which it was being applied. It also important to remember that the kWh/m^3 in Figure 4-31 was assuming that no salt was added to the wastewater in practice coastal areas could add salt to the wastewater thus greatly reducing the energy consumption. Figure 4-32 shows again the TSS data in terms of actual kWh/m^3 consumed. This would be possible if discharging into a marine environment.

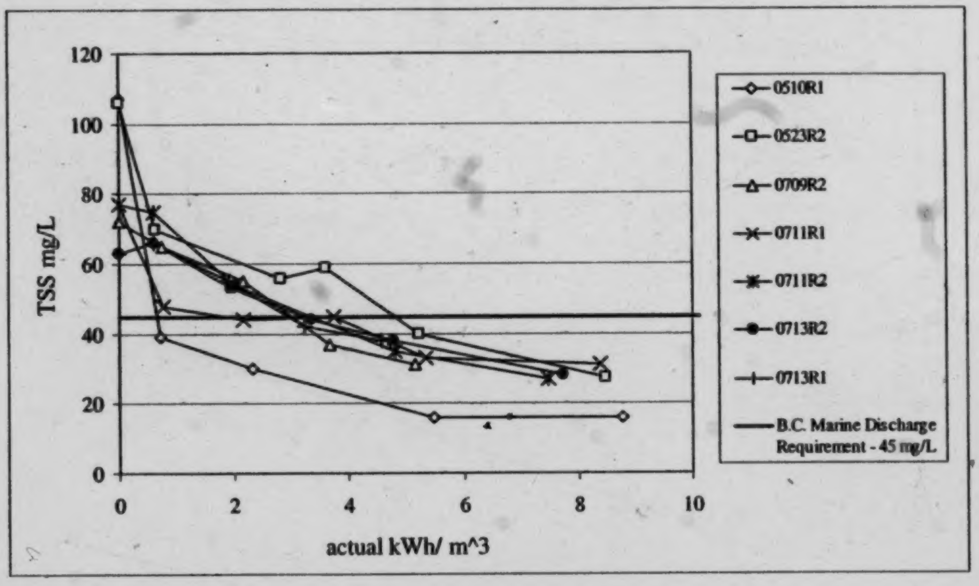

Figure 4-32 Actual Power Consumption Graph for TSS Samples

These energy consumption values are still high but not nearly as high as those seen Figure 4-31.

Another reason why this power consumption may be high is that the current salt addition may allow for amperes in excess of the 62 A limit the test unit was regulated to (i.e. if 100 g / L salt is added the maximum amperes applied would still be 62 A). When calculating this into the equivalent required volts it was not worked into the formula (i.e the average amperes obtained in the example was 55 A which could possibly yield a higher average if not for the test units limit set at 62 amps as higher amperes could have been possible with the given driving volts). Figure 4-3 from the batch test results shows that a conductivity of 4070 µs/cm was required to reach the 62 (A) limit intermittently. The typical conductivity treated for the final testing was 4806 µS/cm and this value was used for the conversion. It was not notably larger than 4070 µS/cm and the extra 736 µS/cm can be assigned to ensure process consistency. That is the test unit should not change amperes up and down all the time. If the amperes were to change to a lower level in the treatment situation then the wastewater would not receive proper treatment while at other times the wastewater. Therefore, the extra conductivity addition used in the calculations is required (i.e. consistent amperes need to be applied to the wastewater). Therefore, the conductivity value used for the calculation is valid as it gives a conservative estimate of the required power consumption if no salt were to be added and provides for consistence performance under these conditions.

It is also important to note that these values are indicative of the power consumption of the electrode only and the ozone generator and pump also consume power through the process, thus increasing the overall cost of the system. It is also interesting to note that based on the metals analysis it was found that the process is adding in excess of 50 mg/L aluminum. Donini et al.(1994) suggests that the aluminum electrode material cost is \$7/kg and at the rate of the average aluminum addition tested of 81 mg/L (83 mg/L final average aluminum concentration in blended treated sample minus 2 mg/L average initial aluminum concentration in the primary effluent) an approximate material cost in terms of cost / m^3 wastewater can be calculated. At an aluminum addition of 81 mg/L the material cost is about \$0.57/m^3 (81 mg/L*\$0.000007/mg = \$0.000567/L = \$0.57 /m^3). The \$7/kg Aluminum price given by Donini et al.(1994) may be a bit high as plate aluminum can be purchased in Edmonton for around \$4.4/kg which is a bit lower than the given value. However, with taxes, delivery charges, and the cost of forming the electrochemical cell the price would be in line with values given by Donini et al. (1994).

4.6 Implications of Results

These results show two main points. First that test unit has difficulty in removing certain parameters particularly BOD_5, COD and ammonia. While for TSS and phosphorus the unit treated the wastewater much better. For microbiological reduction the test unit does in fact provide a significant removal however it is still not enough to allow for safe release to the environment due to the potential public health risks as discussed in section 2.1.2. Table 4-16 shows the performance of the test unit relation to standards in western Canada.

Table 4-16 Parameter Performance

Parameter	Ab. Env. (1)	B.C Marine (2)	Performance (at approx., 400 amperes)
BOD_5 (3)	20 mg/L	45 mg/L	50 to 80 mg/L
COD	(45 mg/L)(5)	(102 mg/L)(5)	130 to 200 mg/L
TSS	20 mg/L	45 mg/L	15 to 45 mg/L
TP	1 mg/L	1 mg/L	0.3 to 0.6 mg/L
pH	6.5 to 8.5	6 to 9	7.8 to 8.2
Ammonia/Nitrogen Forms	(4)	(4)	19 to 24 mg/L ammonia 20 to 26 mg/L TKN

(1) Values given are for large municipalities (municipal population >20,000) for smaller municipalities $CBOD_5$ and TSS are 25 mg/L

(2) Values given are for large MWTP (max. daily flow ≥ 50 m^3/d) with embayed marine waters. Other values are similar.

(3) BOD values refer to $TBOD_5$ for B.C. For Alta., BOD_5 values are as $CBOD_5$

(4) Need assessed on a site specific basis

(5) Assuming $COD/BOD_5 = 2.27$

These results suggest that process improvements are required in order for this technology to be an acceptable treatment alternative. However, it is believed that the unit will never be able treat the soluble portion of the BOD_5 or COD effectively without major alterations to its current design.

The second major finding was the energy consumption of the test unit was quite large in relation to other competing technologies. The addition of salt greatly reduces the operating cost as it reduces the driving volts required for any given amount of amperes applied which directly related to any given level of treatment. This technology would be able to become economic if a suitable low cost salt source was available to raise the conductivity (also the power supply would have to be capable of supplying the additional amperes). The problem for inland releases is there are ecological concerns with releasing salt into freshwater waterways. French (1984) discusses the concerns of salinity in watercourses extensively.

4.7 Applications of Technology

As discussed in section 2.3 there appears to growing trend in Canada towards higher treatment levels especially in regards to improving the treatment levels for marine discharges. Inland releases already show high levels of treatment and therefore for this technology to be adopted it would have to replace an existing technology. For discharges to the Pacific Ocean Figure 2-1 shows that the majority of treatment is still primary treatment with a strong trend toward secondary treatment. Coupling the existing primary system with an Electrofloc^{PLUS} treatment system could be a potential area for the adoption of this technology as the mixing with ocean water would be possible to reduce overall costs of the treatment. Also, as land costs are expensive along the coast the small footprint requirements of the Electrofloc^{PLUS} unit could reduce the capital costs for land. However, a solution to the low overall BOD_5 and COD removals would have to be found before this technology could be fully accepted if these removals remained a key treatment objective. If the key treatment objectives were TSS, TP and microorganism reduction then this unit plus UV (for additional microorganism reduction) may be suitable. Additionally, ensuring consistent performance over all parameters is required.

An alternate suggestion includes applying the electroflocculation process to be part of a chemical/physical wastewater treatment scheme rather than using the process as an all in one secondary treatment process. The results here have shown that COD and TP removals follow a log transformed curve and as such the large initial reductions require relatively small energy requirements.

Other parameters are also quickly reduced such as reduction of organic nitrogen. Designing an overall chemical/physical treatment system incorporating the Electrofloc^{PLUS} system to take advantage of the good initial removals with little energy requirements while avoiding the diminished returns at the higher ampere applied levels would be of value.

Solids separation of microfloc not collected by a bubble may be hindering the performance of the system. Combining the electrofloc system with a microfiltration unit or in a combination using various filter technologies may find a synergistic with the electrofloc treated wastewater. Membrane technology was aided by related electrical technologies as Wakeman (1998) and Houtari et al. (1999) reported.

Additionally the unit has shown excellent phosphorus removals. Perhaps using this system as a tertiary treatment for phosphorus removals could be pursued. Additional testing with secondary effluent would be required to determine the energy requirements and performance with such a waste stream and a phosphorus separation mechanism would have to be determined for this process as the use of flotation may or may not be appropriate in this case.

5.0 Conclusions

This project set out to study the Electrofloc^{PLUS} demonstration treatment system application in the field of municipal wastewater treatment. In this study the determination was based on the results obtained using the Electrofloc^{PLUS} system and its proprietary electrochemical cells and power supply. The test wastewater was Goldbar Wastewater Treatment Plant primary effluent. It was concluded that the system alone was insufficient to treat municipal wastewaters to levels acceptable by the standards outlined by regulating agencies. It was also determined that the system also requires large power inputs to achieve the treatment obtained in the event that salt was not added to system.

This study further defined the capabilities of the test unit, and it found that ozone addition as a coagulant aid did in fact improve process performance. The magnitude of the improvement was small. This study suggests that the ozone had a greater impact when fewer amperes are applied to the wastewater than when the treatment level was more advanced and additional amperes had been applied. The study showed that aluminum electrode was more effective than iron with the wastewater used for the study.

6.0 Recommendations for Further Research

The primary areas for future research involve providing data to further support the use of ozone within the test unit. This research saw slight improvements with the use of ozone (5 to 7% for TP, 3 to 5% for COD and perhaps 6% for TSS) but further research is required to see if the benefits justify its use. The factorial design analysis suggests evidence that the ozone application at the beginning of a test run has a larger impact while diminishing returns exist at higher amperes applied (air may be just as good).

Other future research obviously involves developing and redeveloping different power supplies and electrode arrangements that allow for superior treatment at the same amount of inputs.

Any future research undertaken should be conducted with a test unit with more operational configurability. With more configurability different settings could be investigated allowing for better optimization. The following section outlines recommended test unit modifications required for future research

6.1 Recommended Test Unit Modifications

The primary recommendation for further research would be to improve test unit configurability. The problem with amps applied vs. passes in determining test unit performance was a significant problem and issues such as ozone dose per ampere applied also introduced potential errors and other variables could also have impacted the overall performance of the test unit. The ozone generator should be adjustable to determine the impact of different levels of ozone addition with the equivalent treatment levels rather than having just one level to correlate with the number of passes through the system. If both ozone dose and amperes applied could be keep constant at a specified level but also be easily adjustable to a new level, data that are more comprehensive and that yield better insight into the test unit operations would be possible. In fact with these modifications the test unit overall would be able to yield much more meaningful results much quicker. Also, factors such as flow rate and turbulence in the electrochemical cell impact the overall performance therefore flow rate needs to be adjustable to get better optimization data as different flow rates could be tested and related to performance.

In future research the electrochemical cells must be available for regular inspection so that two things can be identified. The consumption of the cells and the creation of passivation layers should be identified and monitored. The smoothness of the cells also needs to be seen in order to isolate the bubble producing potential of the cells. Also, knowledge of the electrochemical cell size and shaping could greatly aid in modeling the operations of the Electrofloc^{PLUS} system. Not having the electrochemical cells available for inspection makes certain conclusions impossible to be determined. Only the operating cost of the electricity to the electrochemical cell could be determined and the cost of replacing the electrochemical cells was not determined in this study.

Additional driving volts are required as well as the testing from this study found the higher ampere applied levels to be more efficient. As such a higher range of amperes applied could be tested with and without salt addition which was not possible with the test unit used (as it was limited to 62 amperes). This could also lead to finding improved overall performance at any given cumulative applied amperes.

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8.0 Appendix

Appendix A– All Single Pass Test Information

Table A1 – All Single Pass Test Information

Conditions	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Units
Initial volume	26.5	34.1	30.3	18.9	18.9	34.1	24.6	24.6	22.7	22.7	30.3	30.3	Litres
Salt added	70	100	160	70	70	60	65	65	60	60	80	80	grams
Salt added (per Litre)	2.64	2.93	5.28	3.70	3.70	1.76	2.64	2.64	2.64	2.64	2.64	2.64	g/L
Initial conductivity	[illegible]	857	880	1090	1090	925	1070	1070	1070	1070	1090	1090	uS/cm
Test conductivity	4970	8030	8030	6240	6570	3490	5250	5250	5090	4960	5110	5120	uS/cm
Flotation time	60	60	60	60	60	60	60	60	60	60	60	60	min
Sample Collection	2	2	2	2	2	2	2	2	2	2	2	2	L (Jar Test Jar)
Ozone Flow (1)	4-4.5	4.0-4.4	4.0-4.3	4-4.2	4-4.2	4	3.9-4.2	n/a	3.8-4.2	3.9-4.2	3.9-4.1	4.0-4.1	LPM
Ozone Flow (2)	4.1	4.1	4.1	4.1	4.1	4	4.1	n/a	4	4	4	4.1	LPM
Initial Temp	13.6	13	15.4	15.4	15.6	13.8	15.7	15.7	16.3	16.4	14.6	15	C
Final Temp	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	C
Electrode Type	Iron	Iron	Iron	Iron	Iron	Iron	Iron	Iron	Iron	Iron	Iron	Iron	
Approx. Time Collected	Morning	9:00	9:45	12:00	Morning	9:00	11:30	11:30	8:00	8:00	10:45	10:45	
Ozone	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	yes	Yes	No	
Pass	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
1	27	1	52	61	63	26	50	63	50	61	50	53	A
2	46	4	117	123	83	54	100	128	96	121	96	96	A
3	64	6	177	[illegible]	146	104	150	169	153	182	143	152	A
4	65	10	240	[illegible]	209	150	200	215	221	245	200	202	A
5	69	14	302	[illegible]	272	180	252	270	277	309	259	254	A
6	73	19	[illegible]	[illegible]	330	269	311	341	316	372	319	309	A
7	76	24	420	380	385	316	374	404	378	435	379	361	A
8	131	44	480	n/a	n/a	385	433	467	419	493	442	411	A
9	137	68	552	n/a	n/a	440	489	530	455	561	502	446	A
10	142	132	616	n/a	n/a	n/a	548	592	545	624	569	498	A
11	146	148	681	n/a	n/a	n/a	612	668	610	687	631	555	A
Total Amperage Applied³	161	503	744	385	385	440	612	668	610	687	631	555	A
Total Passes	14	16	12	7	7	9	11	11	11	11	11	11	
Average Amps	12	29	62	55	57	49	56	60	55	62	57	50	A
STD Amps	14	30	3	13	13	14	5	11	6	1	6	6	A
% consistent within	71	77	92	71	100	44	18	91	9	100	40	18	
Pass	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
1	0	1	0	1	1	0	0	1	0	1	0	0	
2	0	1	1	1	1	0	0	1	0	1	0	0	
3	0	1	1	1	1	1	0	1	0	1	0	0	
4	1	1	1	0	1	0	0	0	0	1	0	0	
5	1	1	1	0	1	0	0	1	0	1	0	0	
6	1	0	1	1	1	1	0	1	0	1	0	0	
7	1	0	1	1	1	0	0	1	0	1	1	0	
8	1	0	1	n/a	n/a	1	0	1	0	1	1	1	
9	0	1	1	n/a	n/a	1	1	1	0	1	1	0	
10	1	1	1	n/a	n/a	n/a	0	1	1	1	1	0	
11	1	0	1	n/a	n/a	n/a	1	1	0	1	1	1	
Remaining Passes³	3	6	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	
PE	7.44	7.48	7.25	7.39	7.39	7.15	7.2	7.2	7.24	7.24	n/a	n/a	
1	n/a	n/a	7.48	7.67	7.76	n/a	7.58	7.63	7.38	7.71	n/a	n/a	
3	7.68	7.48	7.77	7.82	7.86	7.8	7.8	7.72	7.48	7.72	n/a	n/a	
5	n/a	n/a	7.89	7.79	7.97	7.94	7.86	7.89	7.86	7.8	n/a	n/a	
6	n/a	7.58	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
7	n/a	n/a	7.93	7.83	8.06	8.03	7.79	7.98	7.8	7.97	n/a	n/a	
8	n/a	7.56	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
9	7.86	n/a	8.05	n/a	n/a	8.07	n/a	n/a	n/a	n/a	n/a	n/a	
10	n/a	7.79	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
11	n/a	n/a	n/a	n/a	n/a	n/a	7.94	8.05	7.86	8.05	n/a	n/a	
At final passes³	7.75	7.62	8.12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Total Suspended Solids	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	
PE	76	70	103	83	102	56	83	103	103	83	103	103	mg/L
1	74	n/a	60	53	47	62	65	65	60	56	83	60	mg/L
3	76	68	37	23	45	46	61	64	65	48	73	73	mg/L
5	n/a	n/a	28	36	26	41	50	63	71	37	47	55	mg/L
6	n/a	71	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	n/a	n/a	18	27	22	32	48	42	64	33	46	45	mg/L
8	n/a	75	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
9	63	n/a	17	n/a	n/a	27	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
10	n/a	33	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	n/a	27	13	n/a	n/a	n/a	33	32	47	21	24	31	mg/L
At final passes³	n/a	15	14	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	mg/L
PE	434.9	341.7	365.1	376.5	362.1	342.6	315.6	315.6	421.6	421.6	388.4	388.4	mg/L
1	335.4	n/a	304.0	231.4	225.2	234.6	208.6	186.8	273.0	189.9	286.6	247.0	mg/L
3	341.7	287.3	282.1	209.6	228.3	208.5	198.2	183.6	223.1	202.1	238.6	216.9	mg/L
5	n/a	n/a	259.0	208.6	217.8	209.6	185.7	180.5	205.5	205.5	233.5	204.4	mg/L
6	n/a	281.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	n/a	n/a	246.4	199.2	216.9	183.6	179.4	169.1	192.0	195.1	205.5	192.0	mg/L
8	n/a	215.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
9	291.5	n/a	250.6	n/a	n/a	179.5	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
10	n/a	209.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	n/a	205.6	249.6	n/a	n/a	n/a	169.0	159.7	191.0	179.5	182.0	166.8	mg/L
At final passes³	290.4	189.9	241.2	n/a	n/a	277.2	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
79	382.6	191.0	377.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Total Phosphorus	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	mg/L
PE	5.62	4.79	6.31	5.61	5.63	5.35	6.23	6.16	7.37	7.35	6.62	6.62	mg/L
1	n/a	n/a	3.12	2.20	1.64	2.72	2.71	2.38	4.74	2.49	2.48	3.40	mg/L
3	4.34	n/a	1.01	0.72	1.23	1.49	2.10	1.25	2.97	1.51	1.69	1.80	mg/L
5	n/a	n/a	0.52	0.74	0.44	0.86	1.31	0.93	1.66	0.80	0.73	0.94	mg/L
6	n/a	3.96	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	n/a	n/a	0.33	0.45	0.35	0.53	0.63	0.43	1.39	0.61	0.60	0.61	mg/L
8	n/a	3.61	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
9	2.55	n/a	0.29	n/a	n/a	0.40	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	n/a	0.72	n/a	n/a	n/a	n/a	0.44	0.15	0.60	0.32	0.25	0.38	mg/L
At final passes³	2.32	0.18	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	mg/L
PE	n/a	27.0	24.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
3	n/a	n/a	21.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
6	n/a	23.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	n/a	n/a	21.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	n/a	n/a	21.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
At final passes³	n/a	23.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L

(1) - Flow Range

(2) - Estimated Average

(3) - A few early runs were conducted with greater than 11 passes these values represent the results at the final passes

Table A1 – All Single Pass Test Information (continued)

Conditions	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Units
Initial volume	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	34.1	34.1	Litres
Salt added	80	80	0	0	80	80	80	80	80	80	80	0	80	80	80	grams
Salt added (per Litre)	2.64	2.64	0.00	0.00	2.64	2.64	2.64	2.64	2.64	2.64	2.64	0.00	2.64	2.64	[illegible]	g/L
Initial conductivity	1080	1080	[illegible]	[illegible]	910	910	[illegible]	[illegible]	840	840	[illegible]	[illegible]	[illegible]	1080	[illegible]	uS/cm
Test conductivity	5110	5120	[illegible]	[illegible]	4800	[illegible]	4440	4580	4790	4800	[illegible]	[illegible]	4800	4710	[illegible]	uS/cm
Flotation time	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	min
Sample Collection	2	2	1	2	2	2	2	2	1	2	2	2	2	2	[illegible]	L
Ozone Flow (Flow Range)	3.9-4.1	4.0-4.1	3.7-4.2	3.9-4.1	3.9	3.8-4.0	3.5-3.9	3.7-3.9	3.9-4.1	3.8-3.9	3.9-4.0	3.9-4.0	4	3.9-4.1	4	LPM
Ozone Flow (Estimated Average)	4	4.1	4	4	4.1	3.9	3.8	3.8	4	3.9	4	4	4	4	4	LPM
Initial Temp	14.8	15	12.2	12.5	16.2	16.1	18.4	18.9	17.8	17.4	n/a	[illegible]	n/a	19.1	[illegible]	C
Final Temp	n/a	n/a	n/a	n/a	n/a	n/a	20	n/a	20	n/a	n/a	n/a	n/a	23.2	[illegible]	C
Electrode Type	Iron	Iron	Iron	Iron	Iron	Iron	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	
Approx. Time Collected	10:45	10:45	8:15	8:15	9:00	9:00	Morning	Morning	8:00	8:00	Morning	Morning	Morning	8:10	8:15	
Ozone	Yes	No	No	Yes	Yes	Yes	Yes	No	No	Yes	No	No	Yes	No	Yes	
Pass	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
1	50	53	2	3	16	5	[illegible]	55	[illegible]	[illegible]	0	1	62	[illegible]	[illegible]	A
2	[illegible]	[illegible]	3	6	32	31	117	110	97	[illegible]	0	2	97	[illegible]	[illegible]	A
3	147	[illegible]	4	8	57	60	172	164	154	[illegible]	1	3	142	[illegible]	[illegible]	A
4	[illegible]	[illegible]	5	13	86	87	226	222	208	216	1	4	[illegible]	[illegible]	[illegible]	A
5	[illegible]	254	6	16	121	128	284	287	262	276	1	5	241	301	[illegible]	A
6	318	[illegible]	10	19	159	168	347	346	316	339	1	5	[illegible]	[illegible]	[illegible]	A
7	377	351	12	22	190	205	412	409	377	400	1	6	[illegible]	422	[illegible]	A
8	442	411	16	25	226	[illegible]	482	470	433	462	n/a	n/a	n/a	n/a	n/a	A
9	[illegible]	446	21	28	272	291	542	532	489	524	n/a	n/a	n/a	n/a	n/a	A
10	[illegible]	[illegible]	23	31	322	331	605	594	541	581	n/a	n/a	n/a	n/a	n/a	A
11	631	[illegible]	25	33	351	371	671	630	604	649	n/a	n/a	n/a	n/a	n/a	A
Total Amperes Applied*	631	[illegible]	57	33	561	622	671	630			1	6	340	420	[illegible]	A
Total Passes	11	11	25	11	15	15	11	11	11	11	7	7	7	7	[illegible]	
Average Amps	57	57	2	3	37	42	61	60	55	59	0	1	49	60	[illegible]	A
STD Amps	6	5	1	0	11	15	2	3	4	5	0	0	6	1	[illegible]	A
% consistent within	45	18	0	0	7	27	64	64	9	55	100	100	43	86	57	
Pass	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	
2	0	0	0	0	0	0	1	0	0	0	1	1	0	1	0	
3	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	
4	0	0	0	0	0	0	0	1	0	0	1	1	0	1	1	
5	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	
6	0	0	0	0	0	0	1	0	0	1	1	1	1	1	[illegible]	
7	1	0	0	0	0	0	1	1	1	1	1	1	0	1	[illegible]	
8	1	1	0	0	0	0	1	1	0	1	n/a	n/a	n/a	n/a	n/a	
9	1	0	0	0	0	0	1	1	0	1	n/a	n/a	n/a	n/a	n/a	
10	1	0	0	0	0	0	1	1	0	1	n/a	n/a	n/a	n/a	n/a	
11	1	1	0	0	0	0	1	1	0	1	n/a	n/a	n/a	n/a	n/a	
*12	n/a	n/a	0	n/a	1	4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Pass	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	pH	
PE	n/a	n/a	7.29	7.29	7.1	7.1	6.92	6.91	7.28	7.28	n/a	n/a	n/a	7.7	7.7	
1	n/a	n/a	7.32	7.43	7.29	n/a	7.19	7.13	7.43	7.53	n/a	n/a	n/a	7.87	[illegible]	
3	n/a	n/a	n/a	n/a	n/a	7.64	7.46	7.45	7.77	7.91	n/a	n/a	n/a	8.03	8.02	
5	n/a	n/a	7.48	n/a	7.57	n/a	n/a	n/a	8.04	8.12	n/a	n/a	n/a	8.2	[illegible]	
7	n/a	n/a	n/a	n/a	7.72	7.8	7.91	7.82	8.14	8.25	n/a	n/a	n/a	8.32	[illegible]	
11	n/a	n/a	7.57	7.62	7.67	7.93	8.11	n/a	8.21	8.37	n/a	n/a	n/a	n/a	n/a	
At final passes*	n/a	n/a	7.82	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Parameter	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	TSS	
PE	103	103	102	102	121	121	107	107	108	108	80	80	80	72	72	mg/L
1	92.5	80	80	84	78	n/a	38	36	72	70	50	48	n/a	60	62	mg/L
3	72.5	73.25	n/a	n/a	78	51	38	34	62	58	n/a	n/a	n/a	51	58	mg/L
5	47	56	105	n/a	n/a	n/a	n/a	n/a	58	58	n/a	n/a	n/a	40	37	mg/L
7	46	43	n/a	n/a	51	28	16	22	44	40	50	48	34	32	31	mg/L
11	24.5	31.5	113	108	25	24	16	22	33	27.5	n/a	n/a	n/a	n/a	n/a	mg/L
At final passes*	n/a	n/a	105	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	34	n/a	n/a	mg/L
Pass	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	
PE	388.4	388.4	327.0	327.0	441.0	441.0	431.4	431.4	375.3	375.3	358.2	380.4	380.4	344.2	344.2	mg/L
1	288.6	247.0	174.3	220.0	n/a	n/a	217.9	202.1	264.7	228.6	348.8	323.9	n/a	228.8	172.7	mg/L
3	235.6	218.9	n/a	n/a	338.0	258.0	221.0	236.6	193.0	193.0	n/a	n/a	n/a	194.5	182.1	mg/L
5	233.5	204.4	288.9	n/a	n/a	n/a	n/a	n/a	190.0	185.2	n/a	n/a	n/a	168.1	163.4	mg/L
7	205.5	192.0	n/a	n/a	288.0	225.0	207.0	207.0	171.2	175.8	311.4	282.7	188.3	152.5	180.3	mg/L
11	182.0	188.8	262.6	270.9	215.0	214.0	195.1	199.2	168.0	161.8	n/a	n/a	n/a	n/a	n/a	mg/L
78	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	311.4	n/a	n/a	n/a	n/a	[illegible]	mg/L
Pass	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	
PE	6.62	6.62	n/a	n/a	n/a	n/a	10.22	10.22	12.41	12.41	6.09	6.09	6.09	4.78	4.78	mg/L
1	2.48	3.40	n/a	n/a	n/a	n/a	3.78	6.71	10.28	9.38	6.11	5.33	n/a	2.12	1.44	mg/L
3	1.69	1.80	n/a	n/a	n/a	n/a	n/a	2.78	4.08	2.72	n/a	n/a	n/a	0.78	0.86	mg/L
5	0.77	0.94	n/a	n/a	n/a	n/a	n/a	n/a	2.05	1.90	n/a	n/a	n/a	0.45	0.38	mg/L
7	0.60	0.61	n/a	n/a	n/a	n/a	0.66	0.77	1.04	0.90	5.25	5.59	0.60	0.33	0.33	mg/L
11	0.25	0.38	n/a	n/a	n/a	n/a	0.33	0.38	0.55	0.43	n/a	n/a	n/a	n/a	n/a	mg/L
Pass	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	
PE	n/a	n/a	n/a	n/a	n/a	n/a	26.1	26.1	22.7	22.7	n/a	n/a	n/a	27.5	27.5	mg/L
1	n/a	n/a	n/a	n/a	n/a	n/a	18.8	22.9	21.3	20.3	n/a	n/a	n/a	21.5	17.6	mg/L
3	n/a	n/a	n/a	n/a	n/a	n/a	20.9	21.7	18.7	19.0	n/a	n/a	n/a	23.6	24.4	mg/L
5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	18.7	18.8	n/a	n/a	n/a	23.0	n/a	mg/L
7	n/a	n/a	n/a	n/a	n/a	n/a	21.3	21.5	18.7	18.9	n/a	n/a	n/a	23.8	24.2	mg/L
11	n/a	n/a	n/a	n/a	n/a	n/a	21.3	21.6	18.6	19.0	n/a	n/a	n/a	n/a	n/a	mg/L
Standard (25 mg/L)	n/a	n/a	n/a	n/a	n/a	n/a	25.9	25.9	26.2	26.2	n/a	n/a	n/a	26.0	26.0	mg/L
Pass	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	
PE	n/a	n/a	n/a	n/a	39.5	39.5	35.6	35.6	35.0	35.0	n/a	n/a	n/a	35.7	35.7	mg/L
1	n/a	n/a	n/a	n/a	32.3	n/a	23.7	29.6	29.1	28.1	n/a	n/a	n/a	26.5	20.3	mg/L
3	n/a	n/a	n/a	n/a	33.5	n/a	24.1	25.6	23.0	25.3	n/a	n/a	n/a	27.4	26.6	mg/L
4	n/a	n/a	n/a	n/a	n/a	31.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	24.7	26.4	n/a	n/a	n/a	n/a	n/a	mg/L
7	n/a	n/a	n/a	n/a	29.1	28.4	24.2	26.1	23.7	24.6	n/a	n/a	n/a	28.2	28.6	mg/L
Standard (25 mg/L)	n/a	n/a	n/a	n/a	23.9	23.9	25.8	25.8	27.5	27.5	n/a	n/a	n/a	28.0	28.0	mg/L
Pass	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	
PE	n/a	n/a	n/a	n/a	n/a	n/a	193	193	152	152	n/a	n/a	n/a	146	146	mg/L
1	n/a	n/a	n/a	n/a	n/a	n/a	117	132	90	90	n/a	n/a	n/a	98	36	mg/L
3	n/a	n/a	n/a	n/a	n/a	n/a	110	118	84	81	n/a	n/a	n/a	80	53	mg/L
5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	75	81	n/a	n/a	n/a	75	67	mg/L
7	n/a	n/a	n/a	n/a	n/a	n/a	102	97	76	75	n/a	n/a	n/a	74	71	mg/L
11	n/a	n/a	n/a	n/a	n/a	n/a	101	98	74	69	n/a	n/a	n/a	n/a	n/a	mg/L
78	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	115	n/a	n/a	n/a	n/a	90	mg/L
Glucose-Glutamic check	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	169	169	n/a	n/a	n/a	171	171	mg/L

Table A1 – All Single Pass Test Information (continued)

Conditions	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Units
Initial volume	34.1	30.3	34.1	32.2	34.1	34.1	34.1	30.3	30.3	30.3	30.3	30.3	30.3	30.3	30.3	Liters
Salt added	90	80	90	85	117	117	117	104	160	160	160	160	160	160	160	grams
Salt added (per Litre)	2.64	2.64	2.64	2.64	3.43	3.43	3.43	3.43	5.28	5.28	5.28	5.28	5.28	5.28	5.28	g/L
Initial conductivity	1000	1000	1020	1020	980	980	980	980	980	980	980	980	940	980	980	uS/cm
Test conductivity	4800	4820	4830	4700	5800	5800	5750	5800	8010	8040	8120	8080	8040	8030	8030	uS/cm
Flotation time	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	min
Sample Collection	5	5	3	5	3	3	3	3	3	3	3	3	3	3	3	L
Ozone Flow (Flow Range)	3.9-4.1	3.9-4.1	4.1-4	4.1-4	3.9-4.1	3.9-4.0	4-3.8	3.8-4.0	3.8-4	3.8 to 4	3.8 to 3.9	3.8 to 3.9	3.9	3.9-4.1	3.9-4.1	LPM
Ozone Flow (Estimated Average)	4	4	4	4	4	4	3.9	3.9	3.9	3.9	3.9	3.9	4	4	4	LPM
Initial Temp	19.2	19.5	20.2	20.2	19.1	19.1	18.6	18	n/a	n/a	n/a	n/a	n/a	n/a	n/a	C
Final Temp	n/a	25.6	25.5	24.5	25.1	25	23.1	25.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	C
Electrode Type	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	Aluminum	
Approx. Time Collected	6:30	6:30	6:20	6:20	Morning	Morning	6:15	6:15	[illegible]	8:00	Morning	Morning	Morning	Morning	Morning	
Ozone	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Pass	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
1	[illegible]	47	47	46	[illegible]	[illegible]	51	42	[illegible]	58	58	62	60	62	62	A
2	118	100	97	97	114	116	105	96	98	116	111	109	116	119	119	A
3	165	155	146	150	166	175	143	153	145	176	165	171	175	177	177	A
4	[illegible]	211	195	[illegible]	[illegible]	[illegible]	174	210	201	240	221	[illegible]	[illegible]	231	231	A
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	225	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	A
6	347	[illegible]	257	311	344	[illegible]	263	325	324	384	346	380	345	347	347	A
7	406	[illegible]	[illegible]	[illegible]	403	421	333	367	366	425	405	412	401	405	405	A
8	466	413	n/a	425	n/a	462	n/a	449	n/a	n/a	n/a	n/a	n/a	n/a	n/a	A
9	[illegible]	462	n/a	476	n/a	544	n/a	531	n/a	n/a	n/a	n/a	n/a	n/a	n/a	A
10	584	516	n/a	[illegible]	n/a	606	n/a	563	n/a	n/a	n/a	n/a	n/a	n/a	n/a	A
11	642	571	n/a	[illegible]	n/a	666	n/a	616	n/a	n/a	n/a	n/a	n/a	n/a	n/a	A
Total Amperes Applied	642	571	332	[illegible]	403	666	333	616	n/a	n/a	n/a	n/a	n/a	n/a	n/a	A
Total Passes	11	11	7	11	7	11	7	11	7	7	7	7	7	7	7	
Average Amps	58	52	50	54	58	61	48	56	52	61	58	59	57	58	58	A
STD Amps	4	4	1	2	2	1	6	6	5	2	3	3	2	3	3	A
% consistent within	73	36	57	45	57	82	14	82	57	100	57	86	86	100	100	%
Pass	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
1	0	1	0	1	0	0	0	1	0	1	1	1	1	1	1	
2	0	0	1	1	1	0	0	0	0	1	0	0	1	1	1	
3	0	0	1	1	0	1	0	1	0	1	0	1	1	1	1	
4	1	1	1	0	0	1	0	1	1	1	0	1	1	1	1	
5	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	
6	1	0	0	0	1	1	0	1	1	1	1	1	0	1	1	
7	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	
8	1	0	n/a	0	n/a	1	n/a	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
9	1	0	n/a	0	n/a	1	n/a	0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
10	1	0	n/a	1	n/a	1	n/a	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
11	1	1	n/a	1	n/a	1	n/a	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Pass	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
PE	7.26	7.25	7.23	7.32	7.24	7.27	7.35	7.40	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
1	7.63	7.52	7.83	7.62	7.5	7.71	7.53	7.66	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
3	7.77	7.73	7.71	7.77	7.85	7.76	7.81	7.82	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
5	7.84	8.06	7.83	8.04	7.97	7.87	7.91	8.07	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
7	8.1	8.23	8.09	8.06	8.2	8.05	8.01	8.07	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
11	8.22	8.23	n/a	8.31	n/a	8.26	n/a	8.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	
Parameter	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
PE	77	77	63	63	66	66	66	66	96	96	72	72	n/a	n/a	n/a	mg/L
1	48	75	66	66	90	84	62	67	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
3	44	54	53	53	n/a	61	56	56	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
5	46	n/a	42	44	64	62	43	44	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	33	35	38	38	47	47	41	33	44	41	36	51	n/a	n/a	n/a	mg/L
11	31	27	n/a	25	n/a	44	n/a	23	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
At final passes¹	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Pass	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	COD	
PE	330.1	330.1	336.4	336.4	297.4	297.4	373.8	373.8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
1	154.0	200.8	186.8	168.5	189.2	188.3	246.0	264.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
3	146.2	177.4	187.7	169.6	168.5	169.6	219.5	202.3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
5	170.0	n/a	180.5	155.6	152.5	164.9	208.6	194.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	157.1	164.9	177.4	148.4	161.6	161.8	203.9	183.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	158.7	164.9	n/a	136.9	n/a	144.7	n/a	172.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
70	300.5	299.0	318.1	253.8	269.4	253.8	303.6	355.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Pass	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
PE	4.51	4.51	4.27	4.27	4.46	4.46	5.13	5.13	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
1	1.06	2.24	1.65	1.97	2.41	1.69	1.96	2.52	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
3	0.76	1.06	1.03	0.86	0.73	0.81	1.23	1.12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
5	0.53	n/a	0.55	0.54	0.57	0.46	0.71	0.61	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	0.36	0.46	0.45	0.41	0.36	0.36	0.67	0.44	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	0.30	0.31	n/a	0.56	n/a	0.26	n/a	0.22	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Pass	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	Ammonia	
PE	26.3	26.3	24.1	24.1	24.2	24.2	26.1	26.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
1	17.6	20.1	19.7	14.3	20.3	17.3	23.3	26.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
3	23.1	23.1	21.4	18.9	20.9	21.1	24.1	24.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	n/a	23.0	21.6	18.6	21.0	21.2	24.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	n/a	n/a	n/a	n/a	n/a	n/a	n/a	24.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Standard (25 mg/L)	26.8	26.6	26.5	26.5	26.6	26.6	26.5	26.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Pass	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	TKN	
PE	n/a	n/a	31.1	31.1	32.2	32.2	37.6	37.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
1	n/a	n/a	18.4	14.6	26.0	22.1	22.6	33.5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
3	n/a	n/a	21.8	19.3	24.6	24.8	22.5	29.6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	n/a	n/a	21.3	19.6	24.6	25.4	29.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	n/a	n/a	n/a	n/a	n/a	n/a	n/a	27.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Standard (25 mg/L)	n/a	n/a	23.5	23.5	26.5	26.5	27.0	27.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
Pass	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	BOD	
PE	131	131	145	145	150	150	171	171	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
1	46	70	56	55	61	71	106	119	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
3	52	56	79	67	63	67	93	96	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
5	52	n/a	67	53	57	60	66	65	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
7	56	53	76	53	56	56	88	63	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
11	45	50	n/a	51	n/a	56	n/a	63	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
70	76	69	96	70	96	95	96	110	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L
GL-GL	156	156	142	142	161	161	166	166	n/a	n/a	n/a	n/a	n/a	n/a	n/a	mg/L

(1) Sample for test 0717R1 was actually taken at pass four instead of pass three but results are recorded here as if at pass three

Appendix B – Microbiological Data

Table B1 - Microbiology Data Confidence Limits and Quality Assessment

Fecal Coliforms

Sample		Dilution(10^X)	Replicate a	Replicate b	Replicate c	Average	Variance	D^2	If D^2 is less X^2 (0.05) then no reason to reject the hypothesis that the distribution is Poisson	Representative Count	Arithmetic Average(CFU/100 ml)	Upper Limit (CFU/100 ml)	Lower Limit (CFU/100 ml)
0711	PE	-6	73	74	54	67	127.0	3.79	Poisson	Yes	6.70E+07	7.65E+07	5.75E+07
0711	R1-1	-4	211	331	340	294	5187.0	35.29	Not Poisson	No	2.94E+06	3.14E+06	2.74E+06
0711	R2-1	-4	399	201	352	317	10702.3	67.45	Not Poisson	No	3.17E+06	3.38E+06	2.97E+06
0711	R1-3	-4	148	210	179	179	961.0	10.74	Not Poisson	No	1.79E+06	1.94E+06	1.64E+06
0711	R2-3	-4	249	202	148	200	2554.3	25.59	Not Poisson	No	2.00E+06	2.16E+06	1.83E+06
0711	R1-7	-4	74	138	158	123	1925.3	31.22	Not Poisson	No	1.23E+06	1.36E+06	1.11E+06
0711	R2-7	-4	158	127	89	125	1194.3	19.16	Not Poisson	No	1.25E+06	1.38E+06	1.12E+06
0711	R2-7B	-5	131	150	79	120	1351.0	22.52	Not Poisson	No	1.20E+07	1.33E+07	1.07E+07
0711	R1-7B	-5	108	119	130	119	121.0	2.03	Poisson	No	1.19E+07	1.32E+07	1.06E+07
0718	PE	-6	26	18	10	18	64.0	7.11	Not Poisson	Yes	1.80E+07	2.29E+07	1.31E+07
0718	R1-1	-5	55	64	65	61	30.3	0.99	Poisson	Yes	6.13E+06	7.04E+06	5.23E+06
0718	R2-1	-5	50	55	58	54	16.3	0.60	Poisson	Yes	5.43E+06	6.28E+06	4.58E+06
0718	R1-3	-5	55	41	40	45	70.3	3.10	Poisson	Yes	4.53E+06	5.31E+06	3.76E+06
0718	R2-3	-5	41	51	49	47	28.0	1.19	Poisson	Yes	4.70E+06	5.49E+06	3.91E+06
0718	R1-7	-5	28	34	41	34	42.3	2.47	Poisson	Yes	3.43E+06	4.11E+06	2.76E+06
0718	R2-7	-5	35	27	24	29	32.3	2.26	Poisson	Yes	2.87E+06	3.48E+06	2.25E+06
0718	R1-7B	-6	26	26	23	25	3.0	0.24	Poisson	Yes	2.50E+07	3.08E+07	1.92E+07
0718	R2-7B	-6	20	24	19	21	7.0	0.67	Poisson	Yes	2.10E+07	2.63E+07	1.57E+07
0720	PE	-6	23	28	33	28	25.0	1.79	Poisson	Yes	2.80E+07	3.41E+07	2.19E+07
0720	R1-1	-5	92	92	97	94	8.3	0.18	Poisson	No	9.37E+06	1.05E+07	8.25E+06
0720	R2-1	-5	85	99	89	91	52.0	1.14	Poisson	Yes	9.10E+06	1.02E+07	8.00E+06
0720	R1-5	-5	37	34	30	34	12.3	0.73	Poisson	Yes	3.37E+06	4.04E+06	2.70E+06
0720	R2-11	-4	63	78	63	68	75.0	2.21	Poisson	No	6.80E+05	7.75E+05	5.85E+05
0720	R1-7	-5	35	25	29	30	25.3	1.71	Poisson	Yes	2.97E+06	3.60E+06	2.34E+06
0720	R2-7	-5	30	18	17	22	52.3	4.83	Poisson	Yes	2.17E+06	2.70E+06	1.63E+06
0720	R1-7B	-5	69	102	79	83	286.3	6.87	Not Poisson	No	8.33E+06	9.39E+06	7.28E+06
0720	R2-7B	-5	69	82	92	81	133.0	3.28	Poisson	No	8.10E+06	9.14E+06	7.06E+06

Bacillus subtilis

1128	PE (raw)	-3	13	17	5	12	37.3	6.40	Not Poisson	No	1.17E+04	1.56E+04	7.72E+03
1128	R1-7	-2	12	22	17	17	25.0	2.94	Poisson	Yes	1.70E+03	2.18E+03	1.22E+03
1128	R1-7(blended)	-3	8	6	9	8	2.3	0.61	Poisson	No	7.67E+03	1.09E+04	4.47E+03
1128	PE (spiked)	-5	47	33	51	44	89.3	4.09	Poisson	Yes	4.37E+06	5.13E+06	3.60E+06
1128	R2-7	-4	26	39	31	32	43.0	2.69	Poisson	Yes	3.20E+05	3.85E+05	2.55E+05
1128	R2-7(blended)	-5	18	17	23	19	10.3	1.07	Poisson	Yes	1.93E+06	2.44E+06	1.43E+06
1130	PE-1(spiked)	-5	23	27	24	25	4.3	0.35	Poisson	Yes	2.47E+06	3.04E+06	1.89E+06
1130	R1-7	-4	15	8	13	12	13.0	2.17	Poisson	No	1.20E+05	1.60E+05	8.00E+04
1130	R1-7(blended)	-5	12	14	15	14	2.3	0.34	Poisson	No	1.37E+06	1.79E+06	9.40E+05
1130	PE-2(spiked)	-5	44	48	37	43	31.0	1.44	Poisson	Yes	4.30E+06	5.06E+06	3.54E+06
1130	R2-7	-4	35	28	32	32	12.3	0.78	Poisson	Yes	3.17E+05	3.82E+05	2.52E+05
1130	R2-7(blended)	-5	22	20	30	24	28.0	2.33	Poisson	Yes	2.40E+06	2.97E+06	1.83E+06

Sample Calculations

$$\text{CFU/100mL} = \frac{\text{coliform colonies counted} \times 100}{\text{mL sample filtered}} \qquad \text{0720R1-5 (CFU/100mL)} = \frac{34\ \text{CFU} \times 100}{10^{-5} \times 100\ \text{mL sample filtered}} = 3.4 \times 10^{6}$$

D^2 test

$$D^2 = \frac{(3-1)12.3}{33.7} = 0.73 > \lambda^2(0.05) = 5.99, \text{No Reason to Reject the hypothesis that the distribution is Poisson}$$

Confidence Limits

$$C \pm 2\sqrt{C} = 34 \pm 2\sqrt{34} = 34 \pm 11.7\ \text{CFU}$$

(Then calculate upper and lower CFU/100ml limits as above)

Appendix C - Conductivity Increases from Various Additions of Salt

Table C1 Raw Data for Figure 4-2

Run	Initial Conductivity uS/cm	Grams salt added/ litre wastewater	Final Conductivity uS/cm	Conductivity change uS/cm per mg/L salt added
0215R1	865	2.6	4970	1.6
0220R1	837	2.9	5020	1.4
0222R1	860	5.3	8020	1.4
0228R1	1090	3.7	6240	1.4
0228R2	1090	3.7	6570	1.5
0302R1	925	1.8	3480	1.5
0307R1	1070	2.6	5250	1.6
0307R2	1070	2.6	5250	1.6
0312R1	1070	2.6	5090	1.5
0312R2	1070	2.6	4980	1.5
0314R1	1090	2.6	5110	1.5
0314R2	1090	2.6	5120	1.5
0426R1	910	2.6	4900	1.5
0426R2	910	2.6	4930	1.5
0510R1	890	2.6	4440	1.3
0510R2	890	2.6	4580	1.4
0523R1	840	2.6	4780	1.5
0523R2	840	2.6	4800	1.5
0704R1	964	2.6	4900	1.5
0704R3	964	2.6	4690	1.4
0709R1	1060	2.6	4710	1.4
0709R2	1060	2.6	5000	1.5
0711R1	1000	2.6	4900	1.5
0711R2	1000	2.6	4920	1.5
0713R1	1020	2.6	4930	1.5
0713R2	1020	2.6	4700	1.4
0717R1	950	3.4	5800	1.4
0717R2	950	3.4	5800	1.4
0719R11	980	3.4	5750	1.4
0719R2	980	3.4	5900	1.4
			Average Change	
				1.47

Sample Calculation for 0215R1:

$$\text{Change uS/cm per mg/L salt} = \frac{\text{(Final uS/cm) - (Initial uS/cm)}}{\text{mg salt added / Litre}}$$

$$\text{Change uS/cm per mg/L salt} = \frac{\text{(4970 uS/cm) - (865 uS/cm)}}{\text{2600 mg salt added / Litre}} = 1.6$$

Appendix D – Ampere Applied Variability Measurements Data

Table D1 Measures of Variability of Amperes Applied on Test Passes and Between Test Passes for all Phase 2 Test Runs with a Salt Addition of 2.64 g / L. (Data for Figure 4-5)

Bar (from left to right)	Test Run Code	Electrode Type	Ozone	Salt added per gallon	Initial conductivity	Test conductivity	Total Passes	Average Amperes (A)	Standard Deviation (A	% consistent within
1	0307R2	Iron	Yes	10	1070	5250	11	60	11	91
2	0312R2	Iron	Yes	10	1070	4980	11	62	1	100
3	0314R1	Iron	Yes	10	1090	5110	11	57	6	45
4	0426R1	Iron	Yes	10	910	4900	15	37	11	7
5	0426R2	Iron	Yes	10	910	4930	15	42	15	27
6	0307R1	Iron	No	10	1070	5250	11	56	5	18
7	0312R1	Iron	No	10	1070	5090	11	55	8	9
8	0314R2	Iron	No	10	1090	5120	11	50	6	18
9	0510R1	Aluminum	Yes	10	890	4440	11	61	2	64
10	0523R2	Aluminum	Yes	10	840	4800	11	59	5	55
11	0704R3	Aluminum	Yes	10	964	4690	7	49	8	43
12	0709R2	Aluminum	Yes	10	1060	5000	7	56	1	57
13	0711R1	Aluminum	Yes	10	1000	4900	11	58	4	73
14	0711R2	Aluminum	Yes	10	1000	4920	11	52	4	36
15	0713R1	Aluminum	Yes	10	1020	4930	7	50	1	57
16	0713R2	Aluminum	Yes	10	1020	4700	11	54	3	45
17	0510R2	Aluminum	No	10	890	4580	11	60	3	64
18	0523R1	Aluminum	No	10	840	4780	11	55	4	9
19	0709R1	Aluminum	No	10	1060	4710	7	60	1	86

Appendix E – Metals Analysis Data

Table E1 - Metals Analysis Results

Electrofloc Sample Analysis

Released to: Kai Nielson
Released by: Allan Mumby
Project Leader: Josip Linic
Date of Release: 15-Oct-01

Source	PE			R1-7B			R1-7 SEP			R1-7 Sludge			Detection Limit
Date	20010713	20010717	20010719	20010713	20010717	20010719	20010713	20010717	20010719	20010713	20010717	20010719	
Parameter	0713R1-7	0717R1-7	0719R1-7	0713R1-7	0717R1-7	0719R1-7	0713R1-7	0717R1-7	0719R1-7	0713R1-7	0717R1-7	0719R1-7	
Ag	0.007	0.006	0.006	0.007	0.007	0.004	0.003	0.003	0.002	0.202	0.113	0.150	0.004
Al	1.65	1.69	1.58	70.4	127	51.2	9.16	11.6	10.6	1450	818	1373	0.007
As	0.008	0.008	0.008	0.027	0.036	0.023	0.010	0.010	0.009	0.726	0.610	0.618	0.005
B	0.797	0.566	0.496	0.517	0.548	0.719	0.513	0.477	0.546	0.914	0.825	1.15	0.007
Ba	0.076	0.073	0.070	0.086	0.086	0.072	0.037	0.033	0.037	1.85	1.19	1.58	0.001
Cd	ND	ND	ND	0.002	0.004	0.002	ND	ND	ND	0.118	0.100	0.102	0.002
Cr	0.009	0.033	0.007	0.081	0.114	0.068	0.009	0.011	0.013	2.86	2.31	2.22	0.002
Cu	0.054	0.071	0.046	0.180	0.200	0.347	0.052	0.045	0.040	3.22	1.78	2.29	0.001
Fe	0.46	0.84	0.50	0.53	0.92	0.49	0.12	0.11	0.12	16.32	17.56	14.82	0.005
Hg	ND	ND	ND	0.019	0.024	ND	0.015	ND	ND	0.596	0.488	0.502	0.02
Mn	0.071	0.104	0.084	0.095	0.138	0.091	0.045	0.049	0.056	1.94	1.97	1.80	0.001
Mo	ND	ND	ND	0.027	0.026	ND	ND	ND	ND	0.420	0.316	0.333	0.02
Ni	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.14	0.10	0.12	0.003
Pb	0.012	0.013	0.010	0.026	0.035	0.021	0.006	0.005	0.007	0.752	0.633	0.666	0.005
Se	0.004	ND	0.003	0.034	0.048	0.033	0.005	0.005	0.009	1.13	0.932	0.954	0.004
Tl	ND	ND	ND	0.048	0.048	0.030	ND	ND	ND	1.14	0.932	0.972	0.02
Zn	0.094	0.187	0.105	0.139	0.197	0.140	0.068	0.060	0.063	2.93	3.34	2.96	0.001

Appendix F – Summary of Data for Factorial Design and ANCOVA Analysis

Table F1 – Summary of Data used for Factorial Design and ANCOVA Analysis

Ozone	Electrode	RUN	PASS	Applied Amps	Ln(Amps Applied)	TSS	TSS % Reduction	% Remaining	COD	COD % Reduction	% Remaining	TP	TP % Reduction	% Remaining
No	Iron	0307R1	PE	1	0.000	83	0.0	100.0	315.6	0.0	100.0	6.23	0.0	100.0
No	Iron	0307R1	1	50	3.912	65	21.7	78.3	208.6	33.9	66.1	2.71	56.5	43.5
No	Iron	0307R1	3	150	5.011	61	26.5	73.5	198.2	37.2	62.8	2.1	66.3	33.7
No	Iron	0307R1	5	253	5.533	50	39.8	60.2	185.7	41.2	58.8	1.31	79.0	21.0
No	Iron	0307R1	7	374	5.924	49	41.0	59.0	178.4	43.5	56.5	0.83	86.7	13.3
No	Iron	0307R1	11	612	6.417	33	60.2	39.8	166	47.4	52.6	0.44	92.9	7.1
No	Iron	0312R1	PE	1	0.000	103	0.0	100.0	421.6	0.0	100.0	7.37	0.0	100.0
No	Iron	0312R1	1	50	3.912	80	22.0	78.0	273	35.2	64.8	4.74	35.7	64.3
No	Iron	0312R1	3	158	5.063	85	17.1	82.9	223.1	47.1	52.9	2.97	59.7	40.3
No	Iron	0312R1	5	277	5.622	71	30.5	69.5	205.5	51.3	48.7	1.68	77.2	22.8
No	Iron	0312R1	7	378	5.934	64	37.1	62.9	192	54.5	45.5	1.38	81.3	18.7
No	Iron	0312R1	11	610	6.414	47	54.1	45.9	191	54.7	45.3	0.8	89.1	10.9
No	Iron	0314R2	PE	1	0.000	103	0.0	100.0	388.4	0.0	100.0	6.62	0.0	100.0
No	Iron	0314R2	1	53	3.970	80	22.3	77.7	247	36.4	63.6	3.4	48.6	51.4
No	Iron	0314R2	3	150	5.010	73	28.9	71.1	216.9	44.2	55.8	1.8	72.8	27.2
No	Iron	0314R2	5	254	5.536	55	46.6	53.4	204.4	47.4	52.6	0.94	85.8	14.2
No	Iron	0314R2	7	351	5.860	45	56.3	43.7	192	50.6	49.4	0.61	90.8	9.2
No	Iron	0314R2	11	552	6.313	31	69.4	30.6	188.8	51.4	48.6	0.38	94.3	5.7
Yes	Iron	0307R2	PE	1	0.000	103	0.0	100.0	315.6	0.0	100.0	6.16	0.0	100.0
Yes	Iron	0307R2	1	63	4.143	85	17.1	82.9	186.8	40.8	59.2	2.39	61.2	38.8
Yes	Iron	0307R2	3	189	5.242	64	37.8	62.2	183.6	41.8	58.2	1.25	79.7	20.3
Yes	Iron	0307R2	5	278	5.628	63	39.0	61.0	180.5	42.8	57.2	0.93	84.9	15.1
Yes	Iron	0307R2	7	404	6.001	42	59.0	41.0	168.1	46.7	53.3	0.43	93.0	7.0
Yes	Iron	0307R2	11	656	6.486	33	67.5	32.5	158.7	49.7	50.3	0.15	97.6	2.4
Yes	Iron	0312R2	PE	1	0.000	83	0.0	100.0	421.6	0.0	100.0	7.35	0.0	100.0
Yes	Iron	0312R2	1	61	4.111	58	30.1	69.9	189.9	55.0	45.0	2.49	66.1	33.9
Yes	Iron	0312R2	3	183	5.209	49	41.0	59.0	202.1	52.1	47.9	1.51	79.5	20.5
Yes	Iron	0312R2	5	309	5.733	37	55.4	44.6	205.5	51.3	48.7	0.8	89.1	10.9
Yes	Iron	0312R2	7	435	6.075	33	59.6	40.4	195.1	53.7	46.3	0.61	91.7	8.3
Yes	Iron	0312R2	11	687	6.532	21	74.1	25.9	179.5	57.4	42.6	0.32	95.6	4.4
Yes	Iron	0314R1	PE	1	0.000	103	0.0	100.0	388.4	0.0	100.0	6.62	0.0	100.0
Yes	Iron	0314R1	1	50	3.912	93	10.2	89.8	288.6	25.7	74.3	2.48	62.5	37.5
Yes	Iron	0314R1	3	143	4.965	73	29.6	70.4	236.6	39.1	60.9	1.69	74.5	25.5
Yes	Iron	0314R1	5	258	5.554	47	54.4	45.6	233.5	39.9	60.1	0.73	89.0	11.0
Yes	Iron	0314R1	7	379	5.938	46	55.3	44.7	205.5	47.1	52.9	0.6	90.9	9.1
Yes	Iron	0314R1	11	631	6.448	24	76.2	23.8	192	50.6	49.4	0.25	96.2	3.8
Yes	Aluminum	0510R1	PE	1	0.000	107	0.0	100.0	431.4	0.0	100.0	10.22	0.0	100.0
Yes	Aluminum	0510R1	1	56	4.022	39	63.6	36.4	217.9	49.5	50.5	3.782	63.0	37.0
Yes	Aluminum	0510R1	3	178	5.180	30	72.0	28.0	221	48.8	51.2	2.01	80.0	20.0
Yes	Aluminum	0510R1	7	419	6.038	16	85.0	15.0	207	52.0	48.0	0.661	93.5	6.5
Yes	Aluminum	0510R1	11	671	6.509	16	85.0	15.0	196.1	54.5	45.5	0.334	96.7	3.3
Yes	Aluminum	0523R2	PE	1	0.000	106	0.0	100.0	375.3	0.0	100.0	12.41	0.0	100.0
Yes	Aluminum	0523R2	1	48	3.861	70	34.0	66.0	236.6	37.0	63.0	9.375	24.4	75.6
Yes	Aluminum	0523R2	3	156	5.049	56	47.2	52.8	193	48.6	51.4	2.723	78.1	21.9
Yes	Aluminum	0523R2	5	276	5.621	59	44.3	55.7	185.2	50.7	49.3	1.898	84.7	15.3
Yes	Aluminum	0523R2	7	400	5.992	40	62.3	37.7	175.8	53.2	46.8	0.905	92.7	7.3
Yes	Aluminum	0523R2	11	648	6.474	28	74.1	25.9	161.8	56.9	43.1	0.434	96.5	3.5
Yes	Aluminum	0709R2	PE	1	0.000	72	0.0	100.0	344.2	0.0	100.0	4.78	0.0	100.0
Yes	Aluminum	0709R2	1	56	4.025	65	9.7	90.3	172.7	49.8	50.2	1.44	69.9	30.1
Yes	Aluminum	0709R2	3	166	5.112	55	23.6	76.4	182.1	47.1	52.9	0.86	82.0	18.0
Yes	Aluminum	0709R2	5	281	5.638	37	48.6	51.4	163.4	52.5	47.5	0.38	92.1	7.9
Yes	Aluminum	0709R2	7	394	5.976	31	56.9	43.1	160.3	53.4	46.6	0.33	93.1	6.9
No	Aluminum	0510R2	PE	1	0.000	107	0.0	100.0	431.4	0.0	100.0	10.22	0.0	100.0
No	Aluminum	0510R2	1	55	4.005	56	47.7	52.3	302.1	30.0	70.0	6.706	34.4	65.6
No	Aluminum	0510R2	3	164	5.100	58	45.8	54.2	236.6	45.2	54.8	2.779	72.8	27.2
No	Aluminum	0510R2	7	408	6.011	22	79.4	20.6	207	52.0	48.0	0.767	92.5	7.5
No	Aluminum	0510R2	11	656	6.486	22	79.4	20.6	199.2	53.8	46.2	0.394	96.1	3.9
No	Aluminum	0523R1	PE	1	0.000	106	0.0	100.0	375.3	0.0	100.0	12.41	0.0	100.0
No	Aluminum	0523R1	1	50	3.912	73	31.1	68.9	264.7	29.5	70.5	10.28	17.2	82.8
No	Aluminum	0523R1	3	154	5.036	63	40.6	59.4	193	48.6	51.4	4.082	67.1	32.9
No	Aluminum	0523R1	5	262	5.569	59	44.3	55.7	190	49.4	50.6	2.045	83.5	16.5
No	Aluminum	0523R1	7	377	5.931	44	58.5	41.5	171.2	54.4	45.6	1.038	91.6	8.4
No	Aluminum	0523R1	11	604	6.404	33	68.9	31.1	168	55.2	44.8	0.547	95.6	4.4
No	Aluminum	0709R1	PE	1	0.000	72	0.0	100.0	344.2	0.0	100.0	4.78	0.0	100.0
No	Aluminum	0709R1	1	62	4.119	68	5.6	94.4	208.6	39.4	60.6	2.12	55.6	44.4
No	Aluminum	0709R1	3	180	5.190	51	29.2	70.8	194.5	43.5	56.5	0.78	83.7	16.3
No	Aluminum	0709R1	5	301	5.705	40	44.4	55.6	168.1	51.2	48.8	0.46	90.4	9.6
No	Aluminum	0709R1	7	422	6.044	39	45.8	54.2	152.5	55.7	44.3	0.33	93.1	6.9

Appendix G - Factorial Design Analysis Tables, Figures and Calculation Matrices

Table G1 - Factorial Design Analysis for COD Reduction

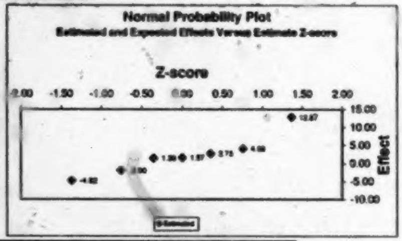
2^3 Factorial Design Analysis COD % Reduction

Factor One	
Name	K(electrode)
Low (-)	A (Iron)
Hi (+)	B (Aluminum)

Factor Two	
Name	C(ozone)
Low (-)	Off
Hi (+)	On

Factor Three	
Name	T(amps aplied)
Low (-)	45-60 (A)
Hi (+)	350-430 (A)

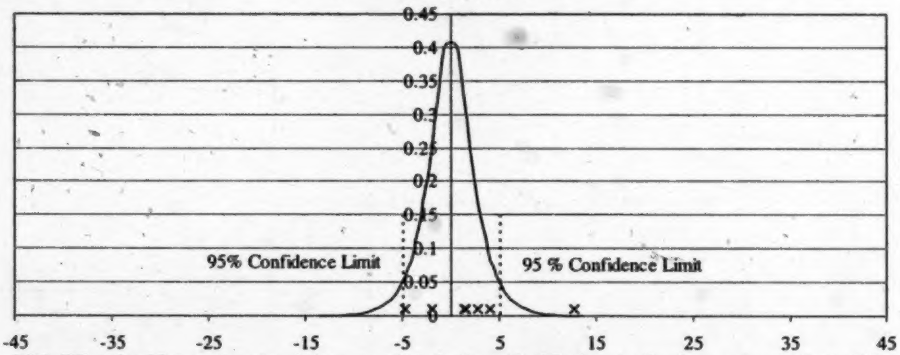
Treatment	Factors			Response Data		
Number	K(electrode)	C(ozone)	T(amps aplied)	Rep 1	Rep 2	Rep 3
1	A (Iron)	Off	45-60 (A)	33.9	35.2	36.4
2	A (Iron)	Off	350-430 (A)	43.5	54.4	50.5
3	A (Iron)	On	45-60 (A)	40.8	55.0	25.7
4	A (Iron)	On	350-430 (A)	46.7	53.7	47.1
5	B (Aluminum)	Off	45-60 (A)	30.0	29.5	39.4
6	B (Aluminum)	Off	350-430 (A)	52.0	54.4	55.7
7	B (Aluminum)	On	45-60 (A)	49.5	37.0	49.8
8	B (Aluminum)	On	350-430 (A)	52.0	53.2	53.4


Normal Probability Plot
Estimated and Expected Effects Versus Estimate Z-score

	Treatment Effect Vectors				Interaction Effect Vectors				Response	
Number	Mean	(electrode	C(ozone)	T(amps aplied)	K * C	K * T	C * T	K * C * T	Means	Vars
1	+	-	-	-	+	+	+	-	35.17	1.56
2	+	-	-	+	+	-	-	+	49.47	30.50
3	+	-	+	-	-	+	-	+	40.50	214.69
4	+	-	+	+	-	-	+	-	49.17	15.45
5	+	+	-	-	-	-	+	+	32.97	31.10
6	+	+	-	+	-	+	-	-	54.03	3.52
7	+	+	+	-	+	-	-	-	45.43	53.36
8	+	+	+	+	+	+	+	+	52.87	0.57
Effect Est.	45.0	2.75	4.083333333	12.86666667	1.56667	1.38333	-4.816666667	-2	Pooled Variance	
Effect SE	1.351645086	2.70329	2.703290176	2.703290176	2.70329	2.70329	2.703290176	2.70329		43.85

Effects and Standard Errors		
Effect	Estimate	SE
Mean	45.0	1.352
K(electrode)	2.75	2.703
C(ozone)	4.083333333	2.703
amps aplie	12.86666667	2.703
K * C	1.566666667	2.703
K * T	1.383333333	2.703
C * T	-4.816666667	2.703
K * C * T	-2	2.703

Normal Probability Plot Data				
Effect	Estimate	Rank	Percentile	Z-Value
K(electrode)	2.75	5.00	0.64	0.35
C(ozone)	4.08	6.00	0.78	0.76
T(amps aplied)	12.87	7.00	0.91	1.36
K * C	1.57	4.00	0.50	0.00
K * T	1.38	3.00	0.36	-0.35
C * T	-4.82	1.00	0.09	-1.36
K * C * T	-2.00	2.00	0.22	-0.76


Chemical Oxygen Demand

Main Effects and Interactions in relation to a *t* distrubution with eight degrees freedom and scale factor 2.7.

Table G2 - Factorial Design Analysis for TP Reduction

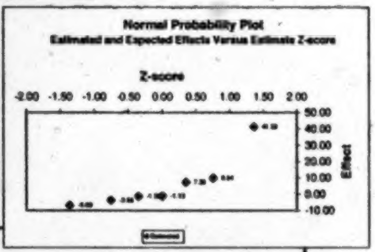
2^3 Factorial Design Analysis TP % Reduction

Factor One	
Name	K(electrode)
Low (-)	A (Iron)
Hi (+)	B (Aluminum)

Factor Two	
Name	C(ozone)
Low (-)	Off
Hi (+)	On

Factor Three	
Name	T(amps aplied)
Low (-)	45-60 (A)
Hi (+)	350-430 (A)

Treatment	Factors			Response Data		
Number	K(electrode)	C(ozone)	T(amps aplied)	Rep 1	Rep 2	Rep 3
1	A (Iron)	Off	45-60 (A)	58.5	35.7	46.6
2	A (Iron)	Off	350-430 (A)	86.7	81.3	90.8
3	A (Iron)	On	45-60 (A)	61.2	66.1	62.5
4	A (Iron)	On	350-430 (A)	93.0	91.7	90.93
5	B (Aluminum)	Off	45-60 (A)	34.4	17.2	55.6
6	B (Aluminum)	Off	350-430 (A)	92.5	91.6	93.1
7	B (Aluminum)	On	45-60 (A)	63.0	24.4	69.9
8	B (Aluminum)	On	350-430 (A)	93.5	92.7	93.1


Normal Probability Plot

Estimated and Expected Effects Versus Estimate Z-score

Data Analysis

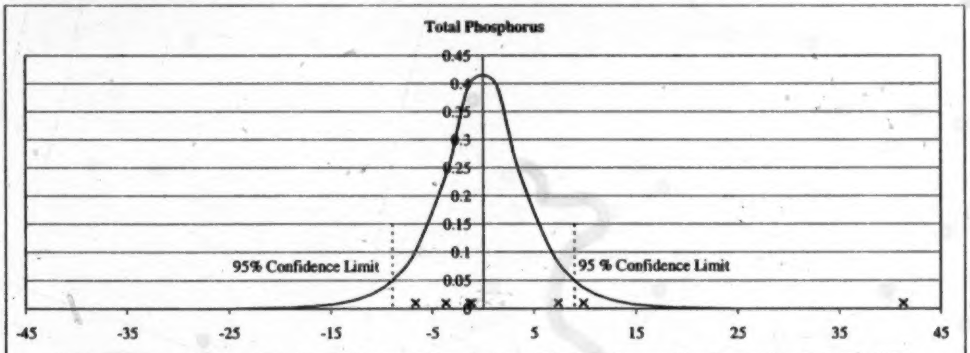
	Treatment Effect Vectors				Interaction Effect Vectors				Response	
Number	Mean	K(electrode)	C(ozone)	T(amps aplied)	K * C	K * T	C * T	K * C * T	Means	Vars
1	+	-	-	-	+	+	+	-	46.93	110.24
2	+	-	-	+	+	-	-	+	86.27	22.70
3	+	-	+	-	-	+	-	+	63.27	6.44
4	+	-	+	+	-	-	+	-	91.88	1.09
5	+	+	-	-	-	-	+	+	35.71	370.76
6	+	+	-	+	-	+	-	-	92.40	0.57
7	+	+	+	-	+	-	-	-	52.43	601.30
8	+	+	+	+	+	+	+	+	93.10	0.16
Effect Est.	70.2	-3.675	9.841666667	41.325	-1.13	7.35333	-6.686666667	-1.325	Pooled Variance	
Effect SE	2.40796537	4.81593074	4.81593074	4.81593074	4.815931	4.81593	4.81593074	4.815931		139.16

Effects and Standard Errors

Effect	Estimate	SE
Mean	70.2	2.408
K(electrode	-3.675	4.816
C(ozone)	9.841666667	4.816
amps aplie	41.325	4.816
K * C	-1.13	4.816
K * T	7.353333333	4.816
C * T	-6.686666667	4.816
K * C * T	-1.325	4.816

Normal Probability Plot Data

Effect	Estimate	Rank	Percentile	Z-Value	Exp Value
K(electrode)	-3.68	2.00	0.22	-0.76	1.36
C(ozone)	9.84	6.00	0.78	0.76	11.69
T(amps aplied)	41.33	7.00	0.91	1.36	15.82
K * C	-1.13	4.00	0.50	0.00	6.53
K * T	7.35	5.00	0.64	0.35	6.93
C * T	-6.69	1.00	0.09	-1.36	-2.76
K * C * T	-1.33	3.00	0.36	-0.35	4.13



Main Effects and Interactions in relation to a t distrubution with eight degrees freedom and scale factor 4.82

Table G3 - Factorial Design Analysis for Percent TSS Reduction

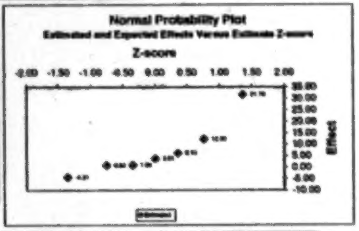
2^3 Factorial Design Analysis TSS % Reduction

Factor One	
Name	K(electrode)
Low (-)	A (Iron)
Hi (+)	B (Aluminum)

Factor Two	
Name	C(ozone)
Low (-)	Off
Hi (+)	On

Factor Three	
Name	T(amps aplied)
Low (-)	45-60 (A)(1 pass)
Hi (+)	350-430 (A)(7 passes)

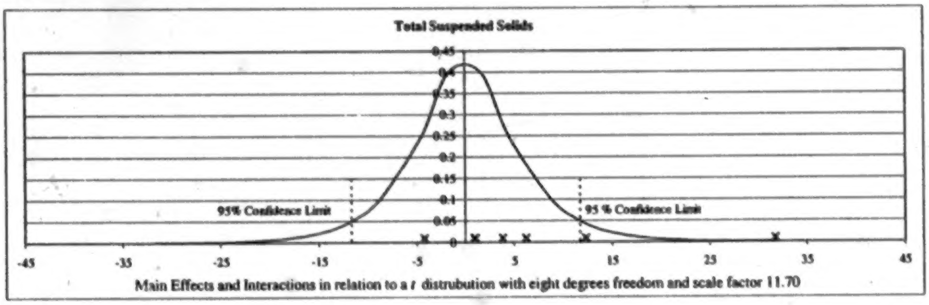
Treatment	Factors			Response Data		
Number	K(electrode)	C(ozone)	T(amps aplied)	Rep 1	Rep 2	Rep 3
1	A (Iron)	Off	45-60 (A)(1 pass)	21.7	22.0	22.3
2	A (Iron)	Off	350-430 (A)(7 passes)	41.0	37.1	56.3
3	A (Iron)	On	45-60 (A)(1 pass)	17.1	30.1	10.2
4	A (Iron)	On	350-430 (A)(7 passes)	59.0	59.6	55.3
5	B (Aluminum)	Off	45-60 (A)(1 pass)	47.7	31.1	5.6
6	B (Aluminum)	Off	350-430 (A)(7 passes)	79.4	58.5	45.8
7	B (Aluminum)	On	45-60 (A)(1 pass)	63.6	34.0	9.7
8	B (Aluminum)	On	350-430 (A)(7 passes)	85.0	62.3	56.9


Normal Probability Plot

Treatment Effect Vectors					Interaction Effect Vectors				Response	
Number	Mean	K(electrode)	C(ozone)	T(amps aplied)	K * C	K * T	C * T	K * C * T	Means	Vars
1	+	-	-	-	+	+	+	-	22.00	0.09
2	+	-	-	+	+	-	-	+	44.80	102.99
3	+	-	+	-	-	+	-	+	19.13	102.10
4	+	-	+	+	-	-	+	-	57.97	5.42
5	+	+	-	-	-	-	+	+	28.13	449.70
6	+	+	-	+	-	+	-	-	61.23	287.84
7	+	+	+	-	+	-	-	-	35.77	728.64
8	+	+	+	+	+	+	+	+	68.07	222.34
Effect Est.	42.1	12.325	6.191666667	31.75833333	1.0417	0.942	3.808333333	-4.2083	Pooled Variance	
Effect SE	3.145052331	6.290105	6.290104663	6.290104663	6.2901	6.29	6.290104663	6.2901		237.39

Effects and Standard Errors		
Effect	Estimate	SE
Mean	42.1	3.145
K(electrode)	12.325	6.290
C(ozone)	6.191666667	6.290
(amps aplie	31.75833333	6.290
K * C	1.041666667	6.290
K * T	0.941666667	6.290
C * T	3.808333333	6.290
K * C * T	-4.208333333	6.290

Normal Probability Plot Data				
Effect	Estimate	Rank	Percentile	Z-Value
K(electrode)	12.33	6.00	0.78	0.76
C(ozone)	6.19	5.00	0.64	0.35
T(amps aplied)	31.76	7.00	0.91	1.36
K * C	1.04	3.00	0.36	-0.35
K * T	0.94	2.00	0.22	-0.76
C * T	3.81	4.00	0.50	0.00
K * C * T	-4.21	1.00	0.09	-1.36


Total Suspended Solids

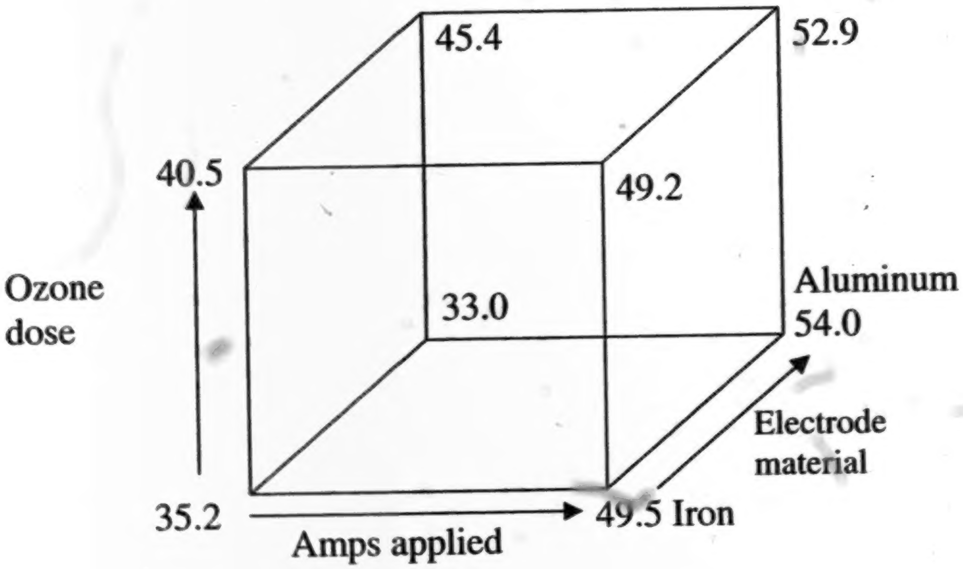


Figure G1 COD Factorial Experiment Box Diagram

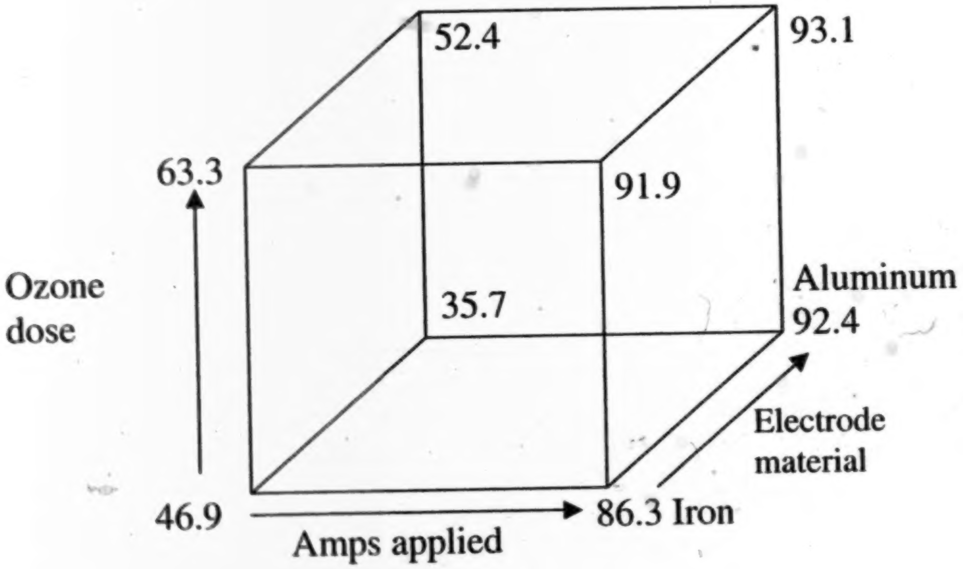


Figure G2 Total Phosphorus Factorial Experiment Box Diagram

Appendix H - Regression Line Analysis

Interpretation of Regression Outputs

The following pages include the regression output analysis from Microsoft Excel 2000 Software. This section will briefly describe the meaning of each key value on the tables.

The ANOVA table is to determine if the slope of the line is significant or not. The df column on the ANOVA table represents the degrees freedom associated with the test, the SS column is the sum of squares total, residual and regression while the MS is the mean square residual and the mean square of the regression. The F value used to test whether the regression lines are significantly greater than zero (i.e. does a significant trend exist).

Mathematically, F = MSRegression/MSResidual.

The Significance F is the resulting P value of whether the slope is significant. If this number is low it indicates that the probability of a statistically significant trend existing is good. When this value is below 0.05 we can say that there is a significant relationship at the 0.05 significance level.

The line estimation table also provides some important information. Most notably for the analysis required here is the P-value (Intercept). This is the resulting P-value calculated from the T-Stat Intercept. When $P \leq 0.05$, then it is established that the y-intercept is significantly greater than zero. The P-value X variable 1 is the same as the significance F discussed above. The Lower 95% and Upper 95% Intercept provides the lower and upper 95% confidence interval for the estimated y-intercept while the Lower 95% - Upper 95% X Variable provides the lower and upper 95% confidence interval for the estimated slope.

The regression statistics also give some valuable information. The "Multiple R" is the sample correlation coefficient and is the square root of R^2. It measures the tightness of fit such that the closer the values are to one the more the x y values are associated. The R square value indicates "coefficient of determination" and explains the percent of variation of the Regression model. The closer the R^2 value is to 1, the better the variation is explained meaning that line describes the observed data clearly (Burt and Barber, 1996). The adjusted R Square is similar to the R^2 only it accounts for the degrees freedom in the model.

The residual plots are very important as well. The residual points should randomly surround 0 in order for the model to be considered adequate. Any trend indicates that the model used is suspect (Burt and Barber, 1996).

First two graphs with regression lines will be shown and then regression analysis for each line will be displayed.

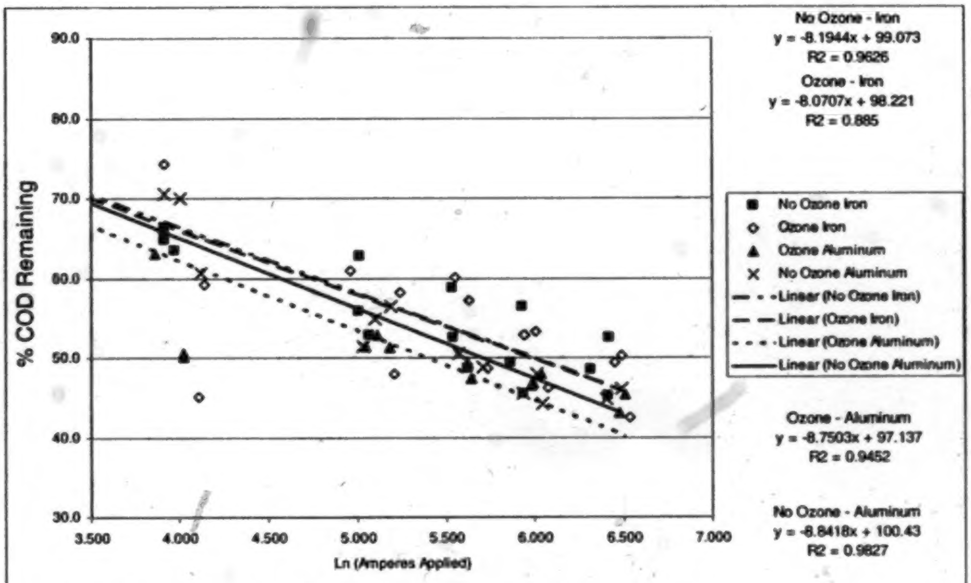


Figure H1 - Percent COD Reduction (Transformed Graph)

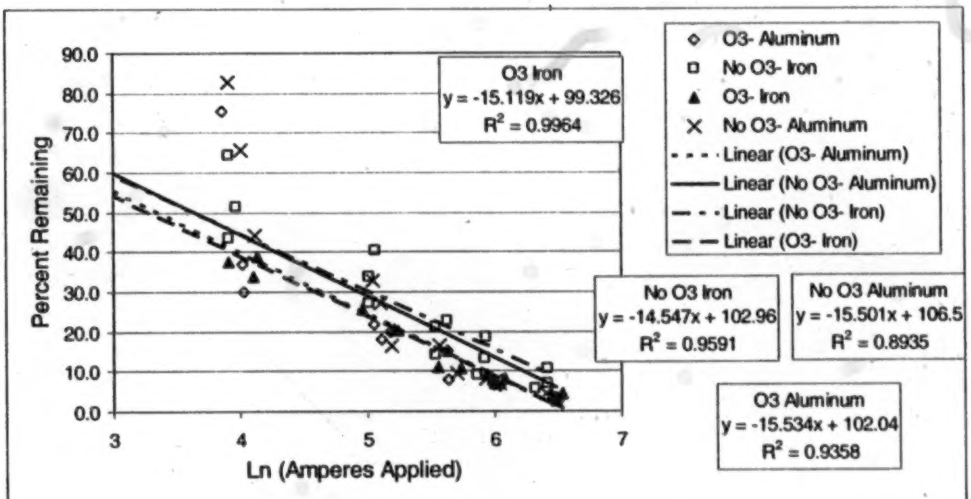


Figure H2 - Percent TP Reduction (Transformed Graph)

Table H1 – Iron Electrode with Ozone for TP Reduction Regression Line Analysis Output

Regression Statistics	
Multiple R	0.99817431
R Square	0.996351953
Adjusted R Square	0.99612395
Standard Error	2.110712567
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	19468.41145	19468.41	4369.908	6.17003E-21	
Residual	16	71.28172066	4.455108			
Total	17	19539.69317				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	99.32558742	1.154346104	86.04489	9.19E-23	96.87848355	101.7726913
X Variable 1	-15.11919728	0.228713907	-66.10528	6.17E-21	-15.604049	-14.63434557

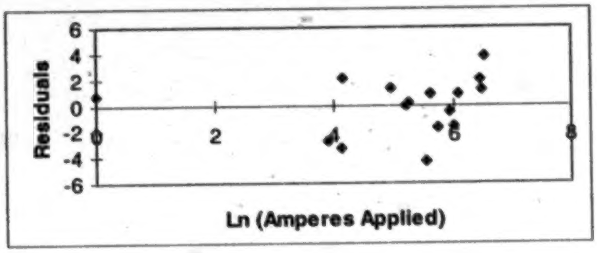


Figure H3 - Iron Electrode with Ozone for TP Reduction Regression Line Residual Plot

From this out put it is seen that the trend is significant as the P-values are very low and the R Square is very near to one which shows that variation is well explained by the regression line. The Residual plots shows no pattern and therefore it is concluded that regression line explains the data well.

Table H2 – Iron Electrode without Ozone Regression Line for TP reductions Analysis Output

Regression Statistics	
Multiple R	0.97934237
R Square	0.959111477
Adjusted R Square	0.956555944
Standard Error	6.820482747
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	17458.94022	17458.94022	375.3079	1.56298E-12
Residual	16	744.3037584	46.5189849		
Total	17	18203.24398			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95.0%*
Intercept	102.9642523	3.720575727	27.67427942	6.1E-15	95.07698583	110.851519
Ln (Applied Amperes)	-14.54725128	0.750908666	-19.37286376	1.56E-12	-16.13910618	-12.9553964

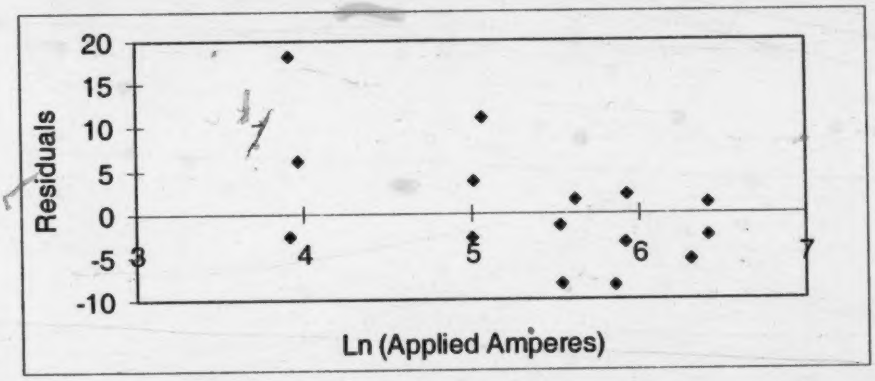


Figure H4 - Iron Electrode without Ozone Regression Line for TP Reductions Residual Plot

From this out put it is seen that the trend is significant as the P-values are very low and the R Square is near to one which shows that variation is well explained by the regression line. The Residual plots shows a small pattern with high residuals at the lower amperes applied levels. Indicating the lines explanation of the data at the low amperes applied may be suspect.

Table H3 – Aluminum Electrode with Ozone Regression Line for TP reductions Analysis Output

Regression Statistics	
Multiple R	0.967359509
R Square	0.935784419
Adjusted R Square	0.931197592
Standard Error	9.704112102
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	19212.10878	19212.11	204.0156	9.70905E-10
Residual	14	1318.377084	94.16979		
Total	15	20530.48587			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	102.0443691	5.310474847	19.21568	1.85E-11	90.65452323	113.4342
X Variable 1	-15.53426321	1.087574323	-14.2834	9.71E-10	-17.86688021	-13.20165

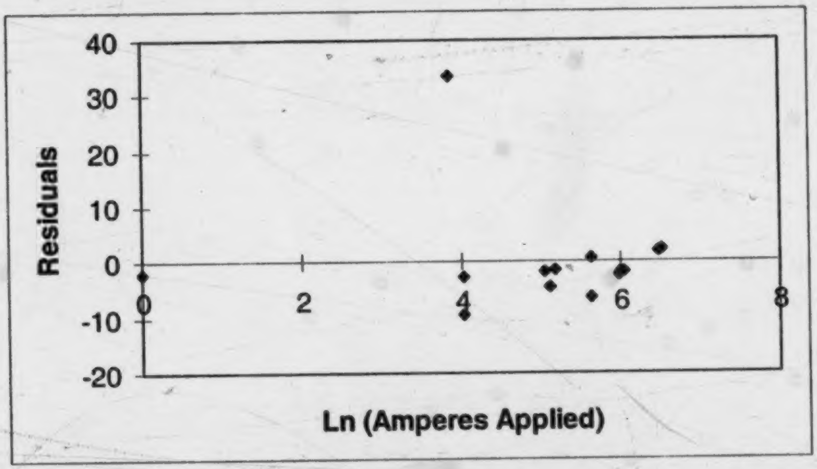


Figure H5 - Aluminum Electrode with Ozone Regression Line for TP Reductions Residual Plot

From this out put it is seen that the trend is significant as the P-values are very low and the R Square is reasonably close to one which shows that variation is well explained by the regression line. The Residual plots shows no pattern and therefore it is concluded that regression line explains the data well.

Table H4 - Aluminum Electrode without Ozone Regression Line for TP Reductions Analysis Output

Regression Statistics	
Multiple R	0.945253455
R Square	0.893504094
Adjusted R Square	0.885897244
Standard Error	12.72076178
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	19007.18969	19007.18969	117.460453	3.41763E-08
Residual	14	2265.448923	161.8177802		
Total	15	21272.63861			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	106.4950906	6.98032978	15.25645549	4.066E-10	91.52375889	121.4664
X Variable 1	-15.50095687	1.43025236	-10.83791735	3.4176E-08	-18.56854582	-12.43337

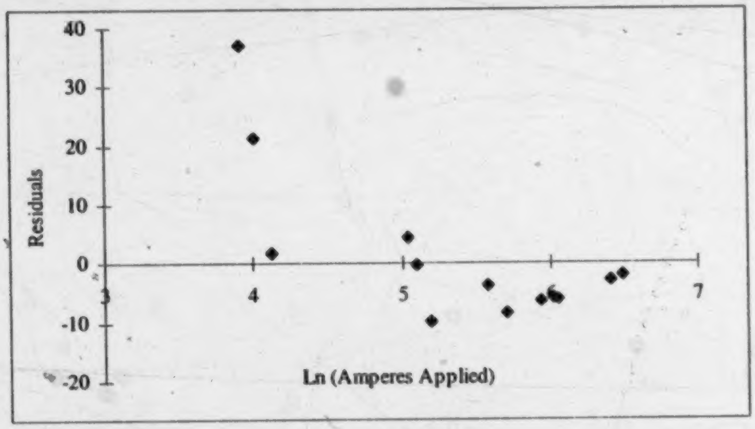


Figure H6 - Aluminum Electrode without Ozone Regression Line for TP Reductions Residual Plot

From this out put it is seen that the trend is significant as the P-values are very low and the R Square is reasonably close to one which shows that variation is somewhat explained by the regression line. The Residual plots show a small pattern with high residuals at the lower amperes applied levels. Indicating the lines explanation of the data at the low amperes applied may be suspect.

Table H5 – Iron Electrode without Ozone Regression Line for COD Reductions Analysis Output

Regression Statistics	
Multiple R	0.981122
R Square	0.962601
Adjusted R Square	0.960264
Standard Error	3.667681
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	5539.773	5539.773	411.8213	7.6437E-13
Residual	16	215.2302	13.45189		
Total	17	5755.003			

	Coefficients	*tandard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	99.07287	2.000721	49.51857	6.14E-19	94.83153283	103.3142
X Variable 1	-8.194416	0.403797	-20.29338	7.64E-13	-9.050427795	-7.338403

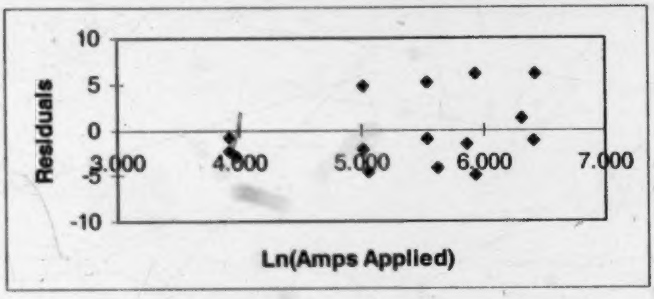


Figure H7 - Iron Electrode without Ozone Regression Line for COD Reductions Residual Plot

From this out put it is seen that the trend is significant as the P-values are very low and the R Square is very near to one which shows that variation is well explained by the regression line. The Residual plots shows no pattern and therefore it is concluded that regression line explains the data well.

Table H6 – Iron Electrode with Ozone Regression Line for COD Reductions Analysis Output

Regression Statistics	
Multiple R	0.940749
R Square	0.885009
Adjusted R Square	0.877822
Standard Error	6.711945
Observations	18

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	5547.542	5547.542	123.1413	6.3365E-09
Residual	16	720.8033	45.05021		
Total	17	6268.345			

	Coefficient	*standard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	98.22137	3.670755	26.75781	1.03E-14	90.43971996	106.003
X Variable 1	-8.070748	0.727297	-11.09691	6.34E-09	-9.612548503	-6.528947

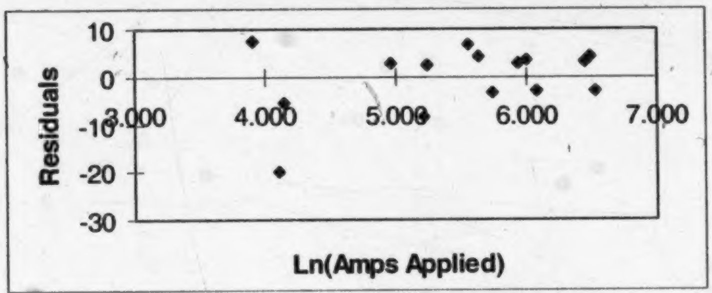


Figure H8 - Iron Electrode with Ozone Regression Line for COD Reductions Residual Plot

From this out put it is seen that the trend is significant as the P-values are very low and the R Square is pretty close to one (0.885) which shows that variation is well explained by the regression line. The Residual plots shows no pattern and therefore it is concluded that regression line explains the data well.

Table H7 – Aluminum Electrode with Ozone Regression Line for COD Reductions Analysis Output

Regression Statistics	
Multiple R	0.972189
R Square	0.945151
Adjusted R Square	0.941234
Standard Error	5.026745
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6095.898	6095.898	241.2481	3.20606E-10
Residual	14	353.7543	25.26817		
Total	15	6449.652			

	Coefficients	*Standard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	97.13654	2.750834	35.31167	4.38E-15	91.23658121	103.0365
X Variable 1	-8.750281	0.563365	-15.53216	3.21E-10	-9.958579936	-7.541982

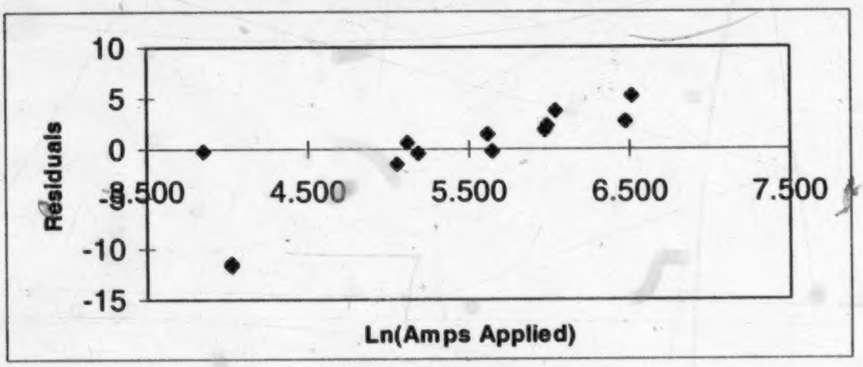


Figure H9 - Aluminum Electrode with Ozone Regression Line for COD Reductions Residual Plot

From this out put it is seen that the trend is significant as the P-values are very low and the R Square is very close to one which shows that variation is well explained by the regression line. The Residual plot perhaps shows a small pattern but it is not that bad so the line will be accepted.

Table H8 – Aluminum Electrode without Ozone Regression Line for COD Reductions Analysis Output

Regression Statistics	
Multiple R	0.991306
R Square	0.982688
Adjusted R Square	0.981451
Standard Error	2.789635
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	6184.205	6184.205	794.6741	9.83839E-14
Residual	14	108.9489	7.782065		
Total	15	6293.154			

	Coefficient	*standard Err*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	100.4261	1.530771	65.60493	7.9E-19	97.14294865	103.7093
X Variable 1	-8.841816	0.313651	-28.18996	9.84E-14	-9.514531994	-8.169101

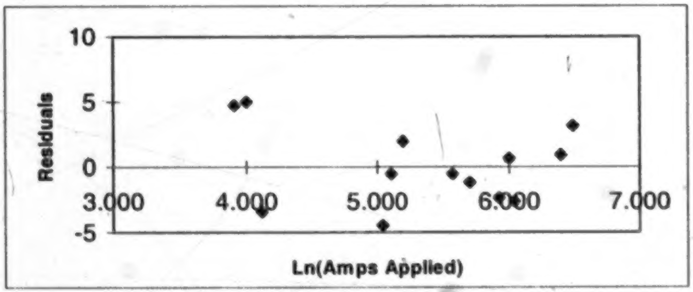


Figure H10 - Aluminum Electrode without Ozone Regression Line for COD Reductions Residual Plot

From this out put it is seen that the trend is significant as the P-values are very low and the R Square is very near to one (0.982) which shows that variation is well explained by the regression line. The Residual plots show no pattern and therefore it is concluded that regression line explains the data well.

Appendix I – Analysis of Covariance (ANCOVA)

The analysis of covariance (ANCOVA) works similarly to the more conventional analysis of variance (ANOVA) the difference being that ANCOVA also incorporates elements of regression analysis. The main idea is to detect differences between two treatment groups (percent reduction) while considering the impacts of the independent covariate (amperes applied). Further discussion on the use of ANCOVA can be found in many advanced statistics textbooks including Winer (1971), Dowdy and Wearden (1983) and Kirk (1982). The primary purpose of ANCOVA is statistical control of variability in situations where experimental control is not possible. In the case of this project it was not possible to hold the amperes applied to a consistent level therefore the use ANCOVA was required for the statistical analysis.

The assumptions of this test include the same assumptions as those used for ANOVA including independence of observations, source populations are normally distributed and homogeneity of variances (for both the dependant variables and covariates). It is felt that data used in this project adequately meets these assumptions to make the results usable. Additionally, ANCOVA requires the assumption the regression lines being compared are approximately the same. In order to determine this, a test for parallel regression lines is used.

The following tables include the results of the ANCOVA analysis, the test for parallel regression lines and also includes an ANOVA test on both the amperes applied and the percent reductions (these are not significantly different in any cases as ANOVA alone is unable to account for differences explained by the covariate). The "PROB" value indicates the probability that the seen difference is due to random chance therefore a low "PROB" value suggests that a significant difference exists. The conclusion uses a 0.05 significance level to determine if a statistically significant relationship exists.

Table I1: ANCOVA Comparing COD % Remaining Curves - Aluminum with Ozone vs. Iron with Ozone

ANALYSIS OF COVARIANCE FOR COMPARING TWO GROUPS

SUMMARY STATISTICS:

	Iron with Ozone	
	% Remaining	Ln(Amps Applied)
Mean	61.465	4.554
Std. Dev.	19.202	2.238
Adj. Mean	62.298	
Sample	18	

	Aluminum with Ozone	
	% Remaining	Ln(Amps Applied)
Mean	59.129	4.344
Std. Dev.	20.736	2.304
Adj. Mean	58.192	
Sample	16	

ANOVA TABLES:

ANOVA on Covariate:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.376	1.000	0.376	0.073	0.789	Covariates Not Different
ERROR	164.782	32.000	5.149			
TOTAL	165.158	33.000				

ANOVA on Dependent Variable:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	46.195	1.000	46.195	0.116	0.735	Depend Variables Not Different
ERROR	12717.998	32.000	397.437			
TOTAL	12764.193	33.000				

Analysis of Covariance (ANCOVA):

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	142.456	1.000	142.456	4.038	0.053	Depend Variables Not Different
ERROR	1093.559	31.000	35.276			
TOTAL	1236.014	32.000				

Test for Parallel Regression Lines:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	19.001	1.000	19.001	0.530	0.472	Likely Regr. Lines are Parallel
ERROR	1074.558	30.000	35.819			
TOTAL	1093.559	31.000				

Table I2: ANCOVA Comparing COD % Remaining Curves - Aluminum Electrodes - without Ozone vs. with Ozone

ANALYSIS OF COVARIANCE FOR COMPARING TWO GROUPS

SUMMARY STATISTICS:

	COD - Aluminum - Ozone	
	% Remaining	Ln(Amps Applied)
Mean	59.129	4.344
Std. Dev.	20.736	2.304
Adj. Mean	59.125	
Sample	16	

	COD - Aluminum - No Ozone	
	% Remaining	Ln(Amps Applied)
Mean	62.012	4.345
Std. Dev.	20.483	2.296
Adj. Mean	62.017	
Sample	16	

ANOVA TABLES:

ANOVA on Covariate:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.000	1.000	0.000	0.000	0.999	Covariates Not Different
ERROR	158.719	30.000	5.291			
TOTAL	158.719	31.000				

ANOVA on Dependent Variable:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	66.499	1.000	66.499	0.157	0.695	Depend Variables Not Different
ERROR	12742.806	30.000	424.760			
TOTAL	12809.305	31.000				

Analysis of Covariance (ANCOVA):

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	66.907	1.000	66.907	4.190	0.050	Depend. Variables Signif. Different
ERROR	463.036	29.000	15.967			
TOTAL	529.943	30.000				

Test for Parallel Regression Lines:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.332	1.000	0.332	0.020	0.888	Likely Regr. Lines are Parallel
ERROR	462.703	28.000	16.525			
TOTAL	463.036	29.000				

Table I3: ANCOVA Comparing COD % Remaining Curves - Iron Electrodes - Without Ozone vs. With Ozone

ANALYSIS OF COVARIANCE FOR COMPARING TWO GROUPS

SUMMARY STATISTICS:

	Iron without Ozone	
	% Remaining	Ln(Amps Applied)
Mean	62.457	4.468
Std. Dev.	18.399	2.203
Adj. Mean	62.108	
Sample	18	

	Iron with ozone	
	% Remaining	Ln(Amps Applied)
Mean	61.465	4.554
Std. Dev.	19.202	2.238
Adj. Mean	61.814	
Sample	18	

ANOVA TABLES:

ANOVA on Covariate:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.066	1.000	0.066	0.013	0.908	Covariates Not Different
ERROR	167.668	34.000	4.931			
TOTAL	167.734	35.000				

ANOVA on Dependent Variable:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	8.868	1.000	8.868	0.025	0.875	Depend Variables Not Different
ERROR	12023.349	34.000	353.628			
TOTAL	12032.216	35.000				

Analysis of Covariance (ANCOVA):

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.776	1.000	0.776	0.027	0.870	Depend Variables Not Different
ERROR	936.674	33.000	28.384			
TOTAL	937.450	34.000				

Test for Parallel Regression Lines:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.641	1.000	0.641	0.022	0.883	Likely Regr. Lines are Parallel
ERROR	936.034	32.000	29.251			
TOTAL	936.674	33.000				

Table I4: ANCOVA Comparing TP % Remaining Curves - Aluminum With Ozone and Aluminum Without Ozone

ANALYSIS OF COVARIANCE FOR COMPARING TWO GROUPS

SUMMARY STATISTICS:

	Aluminum without Ozone	
	% TP remaining Variable - Y	Ln(Amps Applied) X
Mean	39.150	4.345
Std. Dev.	37.659	2.296
Adj. Mean	39.158	
Sample	16	

	Aluminum with Ozone	
	% TP remaining Variable - Y	Ln(Amps Applied) X
Mean	34.571	4.344
Std. Dev.	36.996	2.304
Adj. Mean	34.563	
Sample	16	

ANOVA TABLES:

ANOVA on Covariate:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.000	1.000	0.000	0.000	0.999	Covariates Not Different
ERROR	158.719	30.000	5.291			
TOTAL	158.719	31.000				

ANOVA on Dependent Variable:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	167.798	1.000	167.798	0.120	0.731	Depend Variables Not Different
ERROR	41803.124	30.000	1393.437			
TOTAL	41970.923	31.000				

Analysis of Covariance (ANCOVA):

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	168.942	1.000	168.942	1.367	0.252	Depend Variables Not Different
ERROR	3583.870	29.000	123.582			
TOTAL	3752.812	30.000				

Test for Parallel Regression Lines:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.044	1.000	0.044	0.000	0.985	Likely Regr. Lines are Parallel
ERROR	3583.826	28.000	127.994			
TOTAL	3583.870	29.000				

Table I5: ANCOVA Comparing TP % Remaining Curves - All Runs With Ozone and All Runs Without Ozone

ANALYSIS OF COVARIANCE FOR COMPARING TWO GROUPS

SUMMARY STATISTICS:

	No Ozone	
	% Remaining	Ln (Amperes applied)
Mean	38.521	4.410
Std. Dev.	34.592	2.214
Adj. Mean	38.179	
Sample	34	

	Ozone	
	% Remaining	Ln (Amperes applied)
Mean	32.399	4.455
Std. Dev.	34.908	2.237
Adj. Mean	32.740	
Sample	34	

ANOVA TABLES:

ANOVA on Covariate:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.034	1.000	0.034	0.007	0.934	Covariates Not Different
ERROR	326.893	66.000	4.953			
TOTAL	326.928	67.000				

ANOVA on Dependent Variable:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	637.260	1.000	637.260	0.528	0.470	Depend Variables Not Different
ERROR	79700.608	66.000	1207.585			
TOTAL	80337.868	67.000				

Analysis of Covariance (ANCOVA):

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	502.921	1.000	502.921	7.327	0.009	Depend. Variables Signif. Different
ERROR	4461.824	65.000	68.643			
TOTAL	4964.746	66.000				

Test for Parallel Regression Lines:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	8.339	1.000	8.339	0.120	0.730	Likely Regr. Lines are Parallel
ERROR	4453.486	64.000	69.586			
TOTAL	4461.824	65.000				

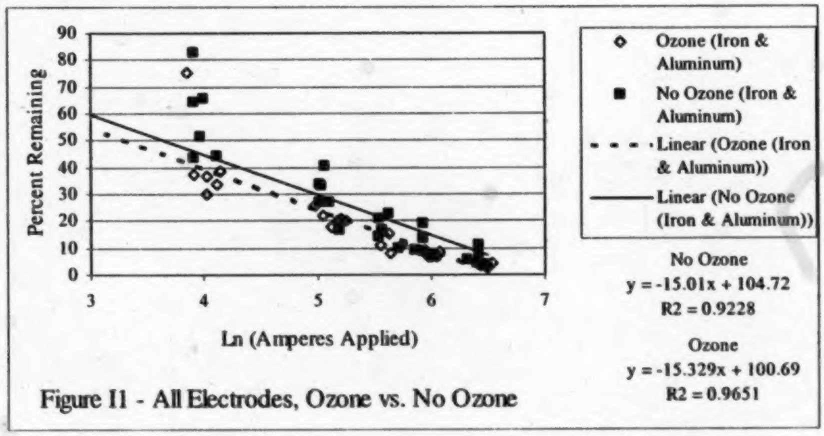


Figure I1 - All Electrodes, Ozone vs. No Ozone

Table I6: ANCOVA Comparing TP % Remaining Curves - Iron Without Ozone and Iron With Ozone

ANALYSIS OF COVARIANCE FOR COMPARING TWO GROUPS

SUMMARY STATISTICS:

	Iron No Ozone	
	% TP remaining Y	Ln(Amps Applied) X
Mean	37.962	4.468
Std. Dev.	32.723	2.203
Adj. Mean	37.324	
Sample	18	

	Iron with Ozone	
	% TP remaining Y	Ln(Amps Applied) X
Mean	30.468	4.554
Std. Dev.	33.903	2.238
Adj. Mean	31.106	
Sample	18	

ANOVA TABLES:

ANOVA on Covariate:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.066	1.000	0.066	0.013	0.908	Covariates Not Different
ERROR	167.668	34.000	4.931			
TOTAL	167.734	35.000				

ANOVA on Dependent Variable:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	505.427	1.000	505.427	0.455	0.504	Depend Variables Not Different
ERROR	37742.937	34.000	1110.086			
TOTAL	38248.364	35.000				

Analysis of Covariance (ANCOVA):

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	347.892	1.000	347.892	13.844	0.001	Depend. Variables Signif. Different
ERROR	829.294	33.000	25.130			
TOTAL	1177.186	34.000				

Test for Parallel Regression Lines:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	13.708	1.000	13.708	0.538	0.469	Likely Regr. Lines are Parallel
ERROR	815.585	32.000	25.487			
TOTAL	829.294	33.000				

Table I7: ANCOVA Comparing TSS % Remaining Curves - Aluminum Without Ozone and Aluminum With Ozone

ANALYSIS OF COVARIANCE FOR COMPARING TWO GROUPS

SUMMARY STATISTICS:

	Aluminum without Ozone	
	% TSS remaining Variable - Y	Ln(Amps Applied) X
Mean	61.204	4.345
Std. Dev.	26.597	2.296
Adj. Mean	61.209	
Sample	16	

	Aluminum with Ozone	
	% TSS remaining Variable - Y	Ln(Amps Applied) X
Mean	55.857	4.344
Std. Dev.	29.965	2.304
Adj. Mean	55.852	
Sample	16	

ANOVA TABLES:

ANOVA on Covariate:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.000	1.000	0.000	0.000	0.999	Covariates Not Different
ERROR	158.719	30.000	5.291			
TOTAL	158.719	31.000				

ANOVA on Dependent Variable:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	228.745	1.000	228.745	0.285	0.597	Depend Variables Not Different
ERROR	24079.522	30.000	802.651			
TOTAL	24308.268	31.000				

Analysis of Covariance (ANCOVA):

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	229.644	1.000	229.644	0.989	0.328	Depend Variables Not Different
ERROR	6736.709	29.000	232.300			
TOTAL	6966.353	30.000				

Test for Parallel Regression Lines:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	41.671	1.000	41.671	0.174	0.680	Likely Regr. Lines are Parallel
ERROR	6695.037	28.000	239.108			
TOTAL	6736.709	29.000				

Table I8: ANCOVA Comparing TSS % Remaining Curves - Aluminum With Ozone and Iron With Ozone

ANALYSIS OF COVARIANCE FOR COMPARING TWO GROUPS

SUMMARY STATISTICS:

	Aluminum No Ozone	
	% TSS remaining Variable - Y	Ln(Amps Applied) X
Mean	60.757	4.554
Std. Dev.	25.521	2.238
Adj. Mean	61.808	
Sample	18	

	Aluminum with Ozone	
	% TSS remaining Variable - Y	Ln(Amps Applied) X
Mean	55.857	4.344
Std. Dev.	29.965	2.304
Adj. Mean	54.674	
Sample	16	

ANOVA TABLES:

ANOVA on Covariate:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	0.376	1.000	0.376	0.073	0.789	Covariates Not Different
ERROR	164.782	32.000	5.149			
TOTAL	165.158	33.000				

ANOVA on Dependent Variable:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	203.376	1.000	203.376	0.265	0.610	Depend Variables Not Different
ERROR	24541.159	32.000	766.911			
TOTAL	24744.534	33.000				

Analysis of Covariance (ANCOVA):

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	430.105	1.000	430.105	2.211	0.147	Depend Variables Not Different
ERROR	6031.556	31.000	194.566			
TOTAL	6461.661	32.000				

Test for Parallel Regression Lines:

SOURCES	SS	DF	MS	F	PROB	Conclusion
BETWEEN GROUPS	20.563	1.000	20.563	0.103	0.751	Likely Regr. Lines are Parallel
ERROR	6010.993	30.000	200.366			
TOTAL	6031.556	31.000				